Penning Traps
&
Neutrino Mass

Sergey Eliseev
Division “Stored and Cooled Ions” (Prof. K. Blaum)
Max-Planck-Institute for Nuclear Physics, Germany

6th Symposium on Neutrinos and Dark Matter in Nuclear Physics ,Daejeon, South Korea

Determination of neutrino mass with a sub-eV uncertainty

KATRIN - Project
Project 8

β^--decay of Tritium

ECHo - Project

HOLMES - Project

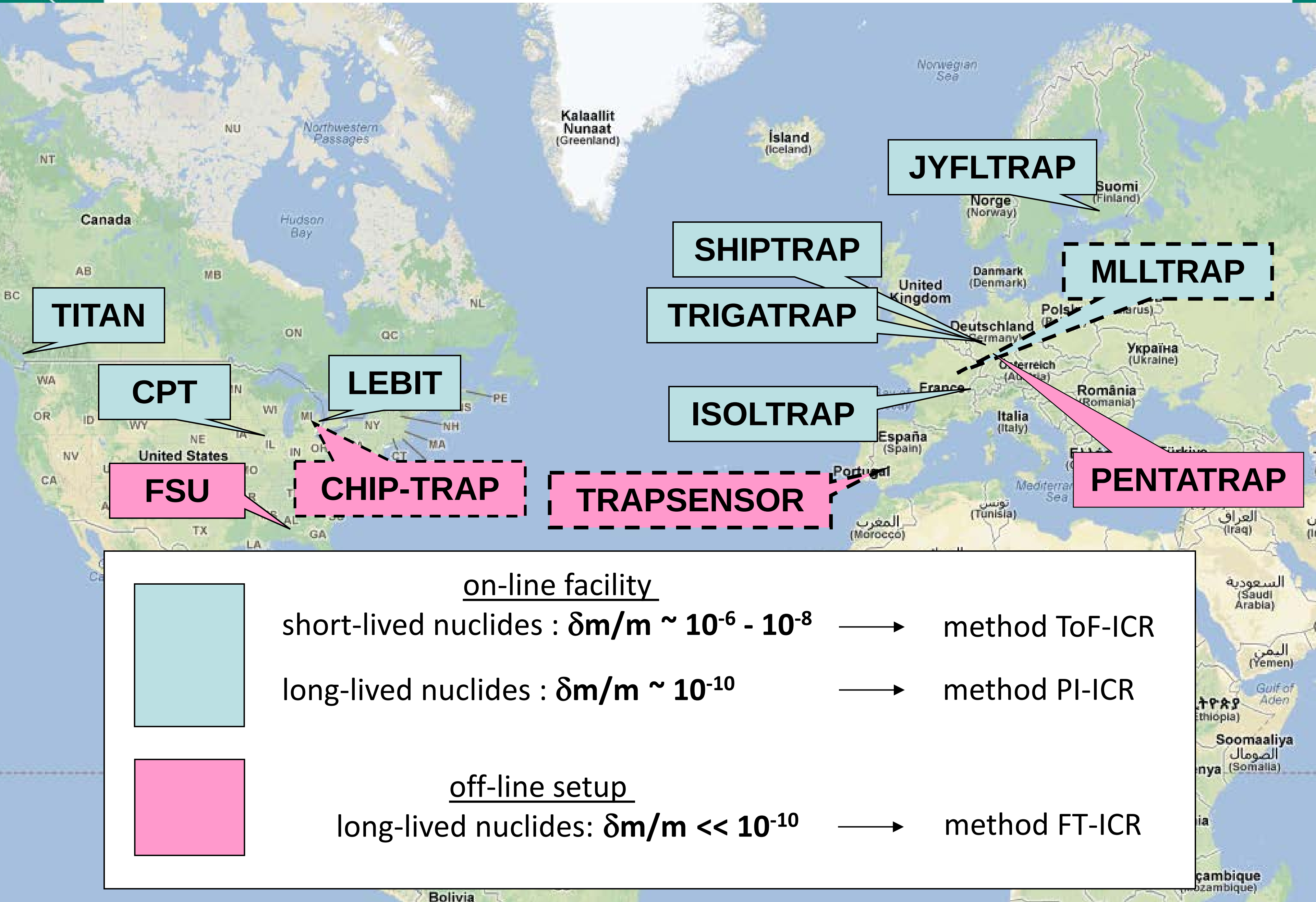
EC in ^{163}Ho

*Q*_Penning trap $\xleftrightarrow{\text{comparison}}$ *Q*_experiment

(δQ/m) < 10^{-11}

Independent test of systematic uncertainty in $\mathbf{m_\nu}$ determination

Penning-Traps worldwide



<u>on-line facility</u>

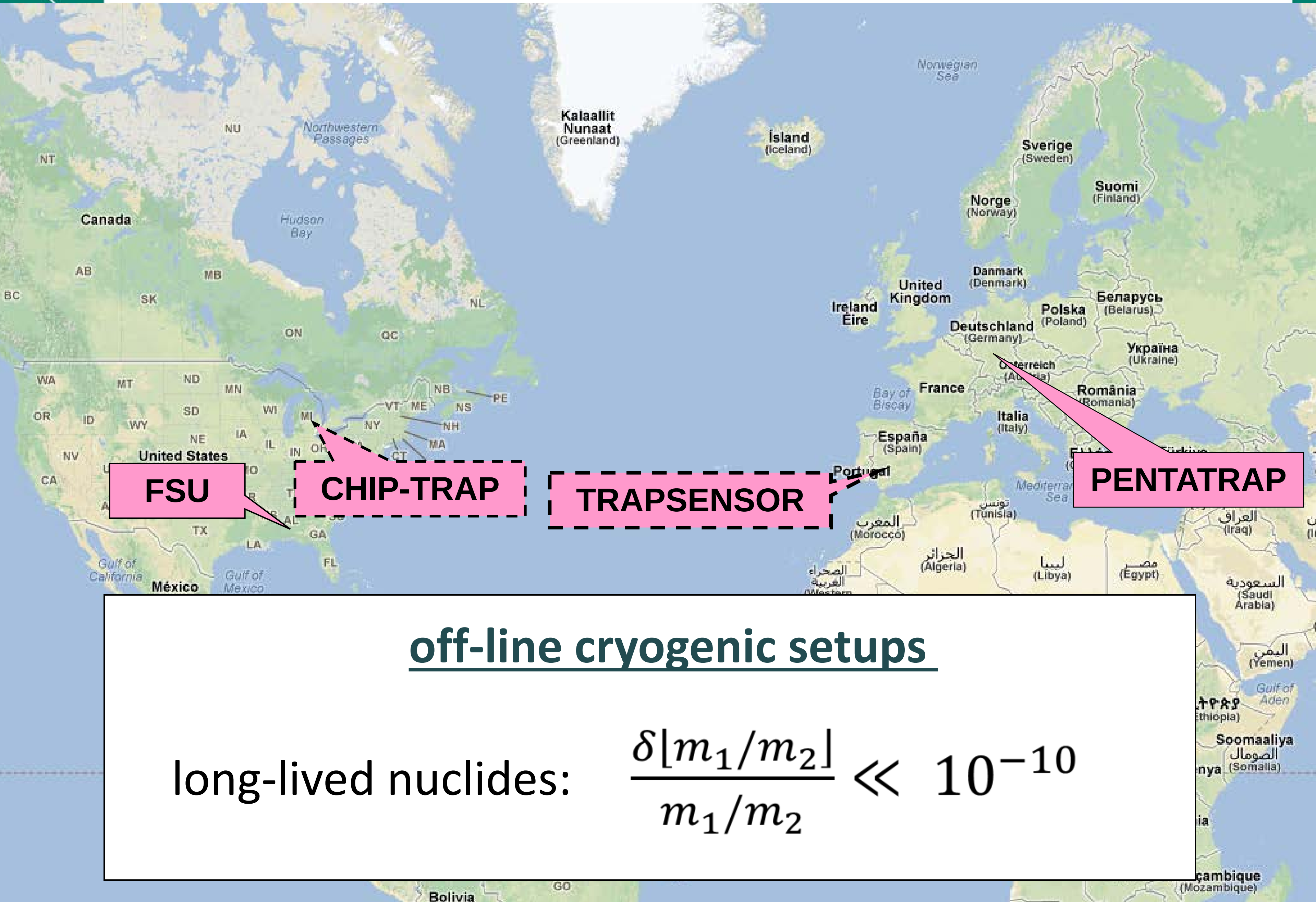
short-lived nuclides : **$\delta m/m \sim 10^{-6} - 10^{-8}$** → method ToF-ICR

long-lived nuclides : **$\delta m/m \sim 10^{-10}$** → method PI-ICR

<u>off-line setup</u>

long-lived nuclides: **$\delta m/m \ll 10^{-10}$** → method FT-ICR

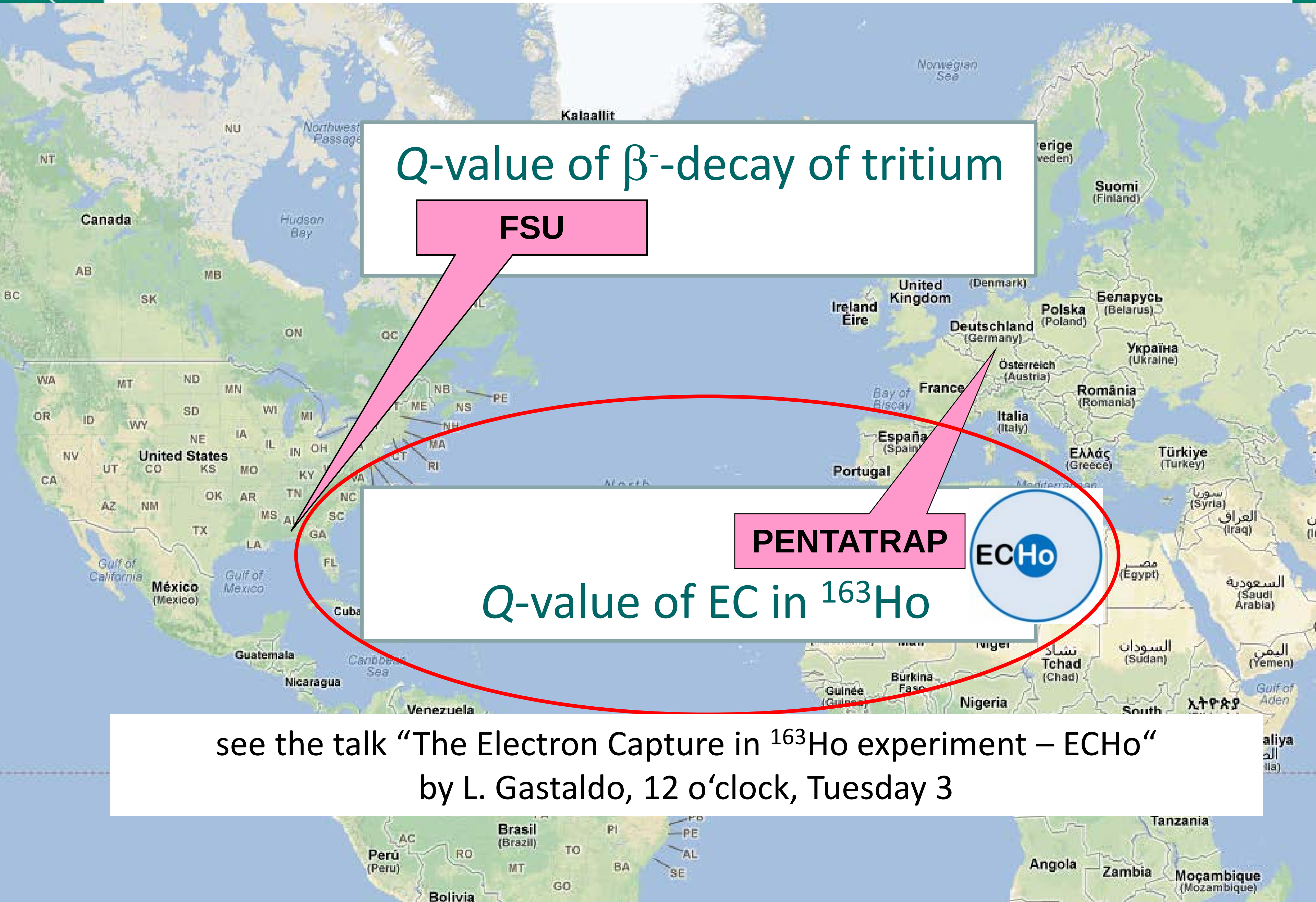
Penning-Traps worldwide



off-line cryogenic setups

long-lived nuclides: $\frac{\delta[m_1/m_2]}{m_1/m_2} \ll 10^{-10}$

Penning-Traps for neutrino mass



Q-value of β^--decay of tritium

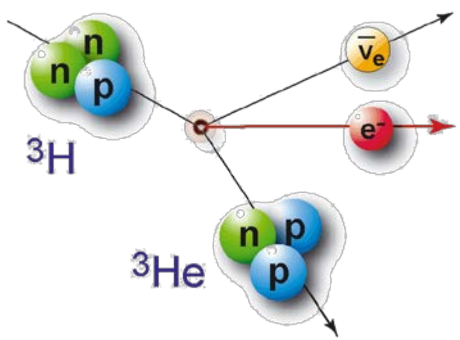
Q-value of EC in ^{163}Ho

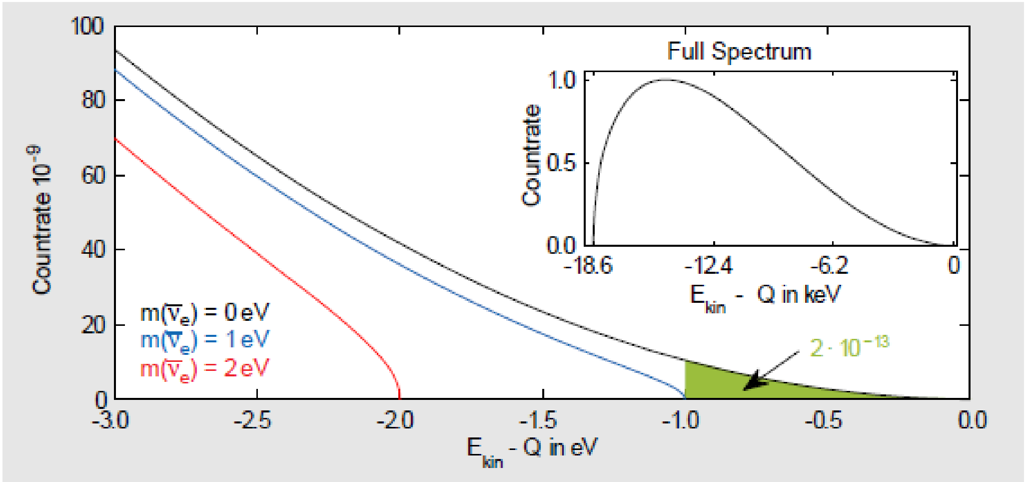
see the talk “The Electron Capture in ^{163}Ho experiment – ECHo“
by L. Gastaldo, 12 o‘clock, Tuesday 3

Q-value of β^--decay of tritium

"**Project 8:** Towards using Cyclotron Radiation ...." by G. Rybka, 16:30, Tuesday 3

"Status of the **KATRIN** experiment ...." by Wonqook CHOI, 17:30, Tuesday 3





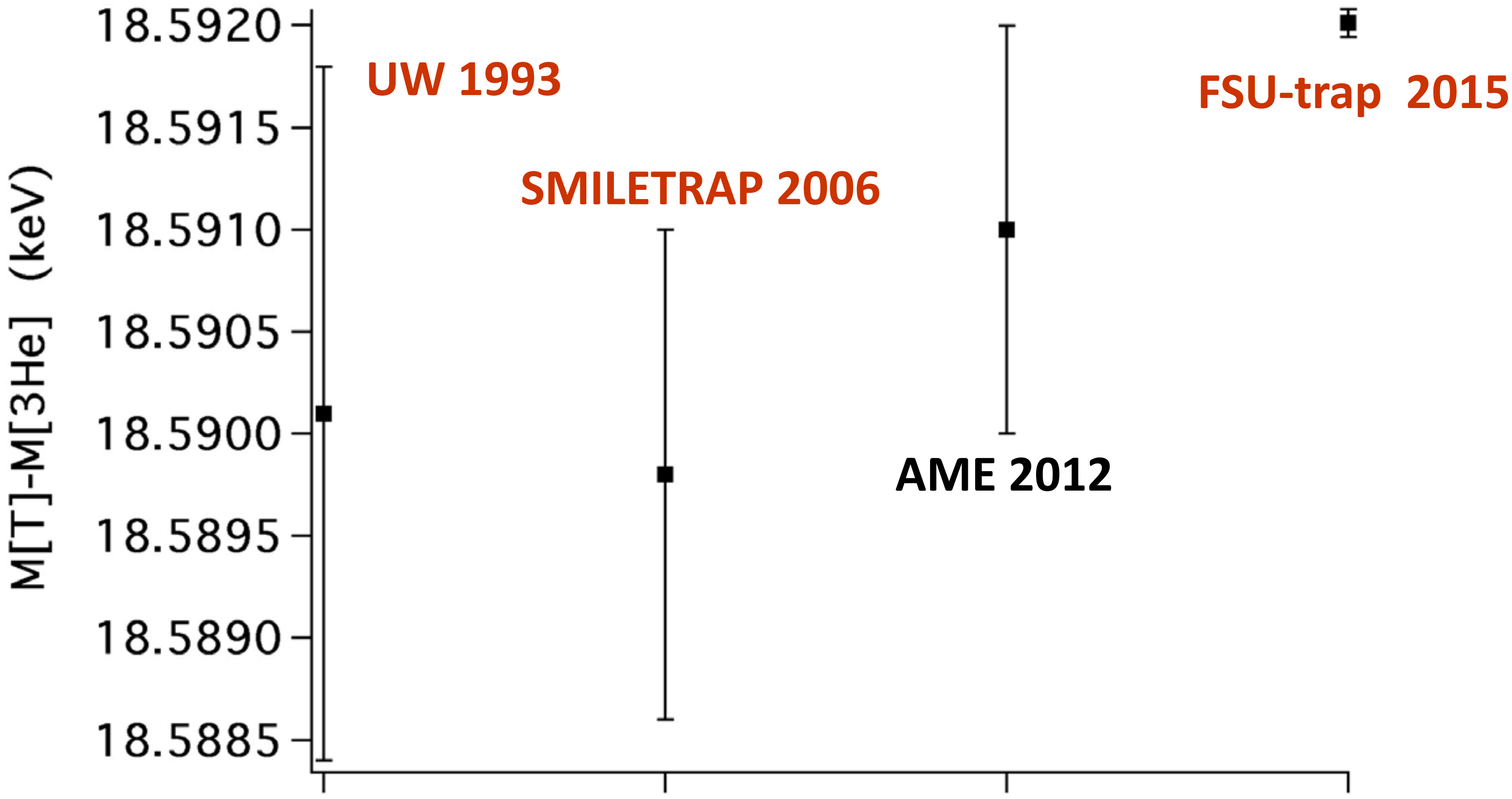
Goal for Penning Traps: $\delta Q \approx$ a few meV

Q from Fit $\xleftrightarrow{\text{comparison}}$ Q from Penning traps

⇩

Independent test of systematics for m_ν

Q-value of β^--decay of tritium



FSU-trap 2015: (18 592.01 ± 0.07) eV

E. G. Myers *et al.*, PRL 114 (2015) 013003

To do at FSU

System Upgrade:
New SQUID: reduce detector noise and ion temperature.
Reduce magnetic field inhomogeneity.
Increase magnetic field stability.
Use larger radius orbit for parked ion.

Measure stable ions:
$^3He^+/HD^+$ (again), $^3He^+/H_3^+$; HD^+/H_3^+

Then:
T^+/HD^+, T^+/H_3^+;

$T^+/^3He^+$ directly

Re-implement coupled magnetron method.

taken from Ed. Myers' talk at ECT* 2016

MAX PLANCK INSTITUTE FOR NUCLEAR PHYSICS

PENTATRAP

Q-value of EC in ^{163}Ho

Prof. Klaus Blaum

Spokesperson – Dr. Sergey Eliseev

ECHo

Kirchhoff-Institute for Physics, Heidelberg University, Germany

Prof. Christian Enss

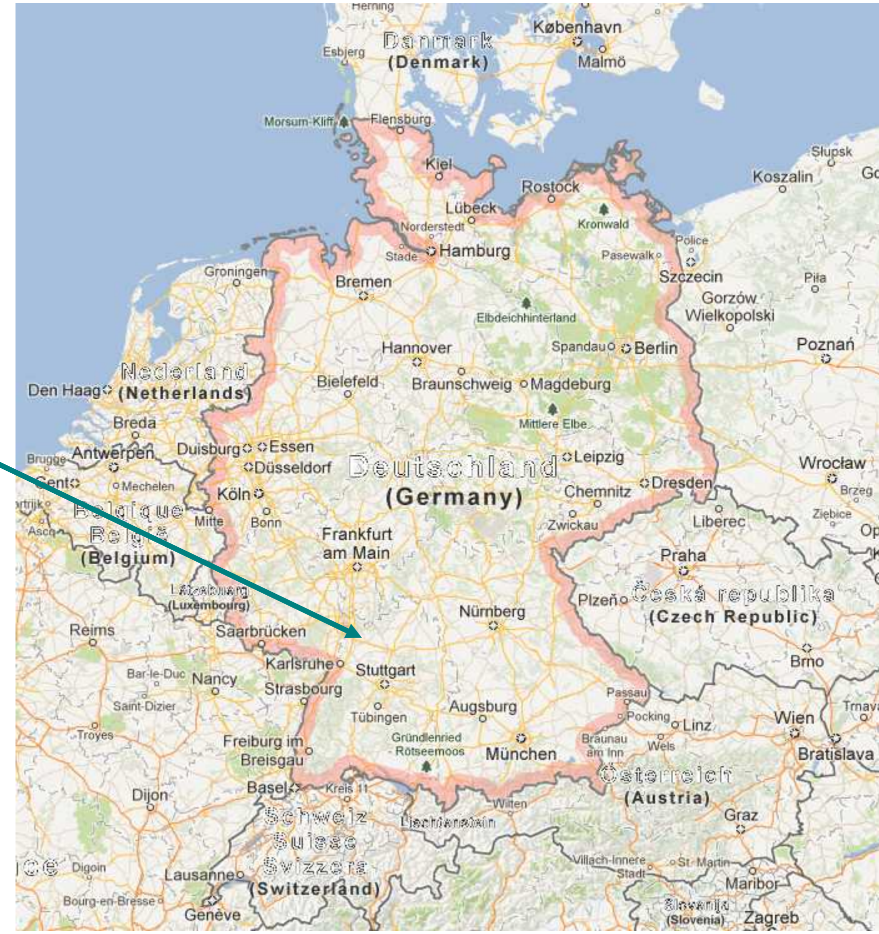
Spokesperson – Dr. Loredana Gastaldo

see the talk “The Electron Capture in ^{163}Ho experiment – ECHo“
by L. Gastaldo, 12 o‘clock, Tuesday 3

Location of PENTATRAP

Max-Planck Institute for Nuclear Physics
(Heidelberg)

Division “Stored and Cooled Ions”
(Prof. Blaum)



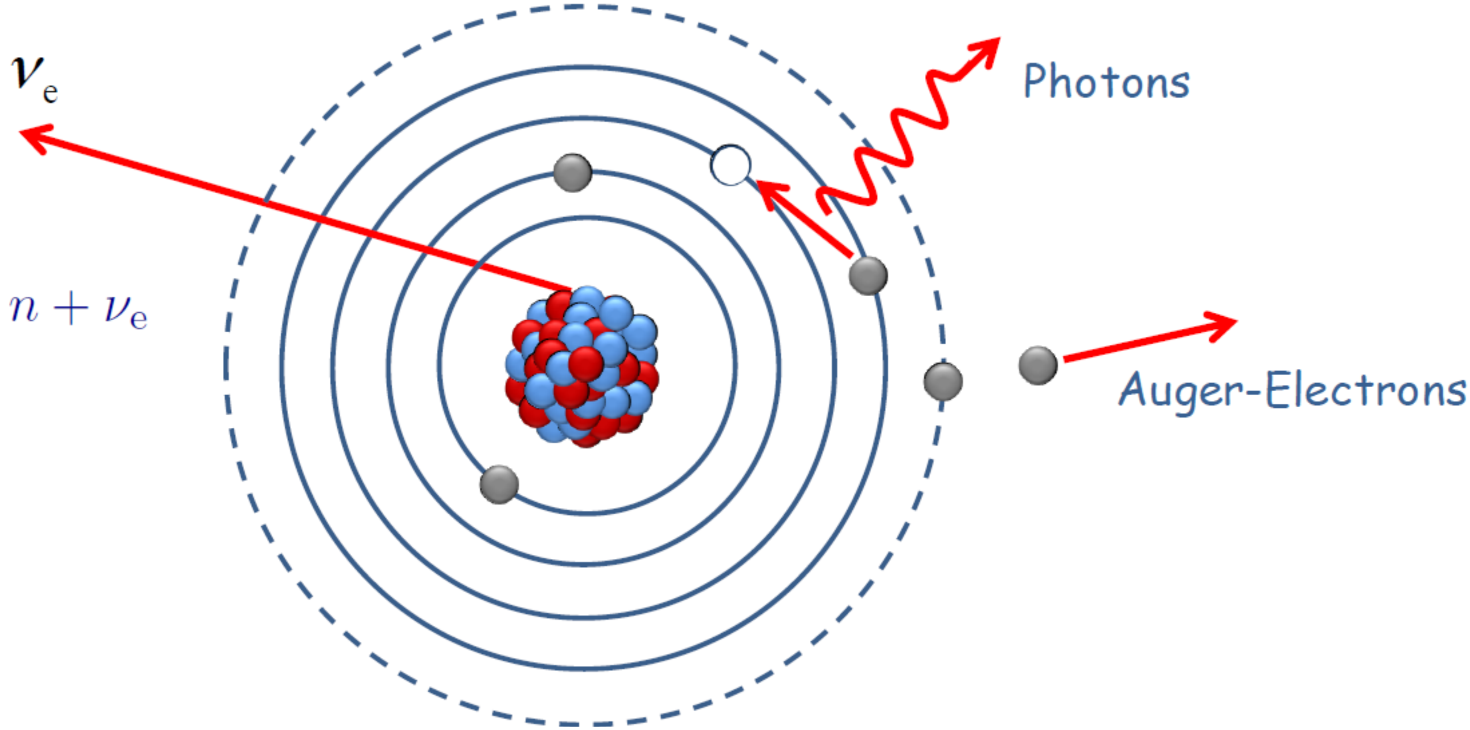
measurements of mass ratios of long-lived and stable nuclides up to uranium with an uncertainty $< 10^{-11}$

Electron Capture: ^{163}Ho

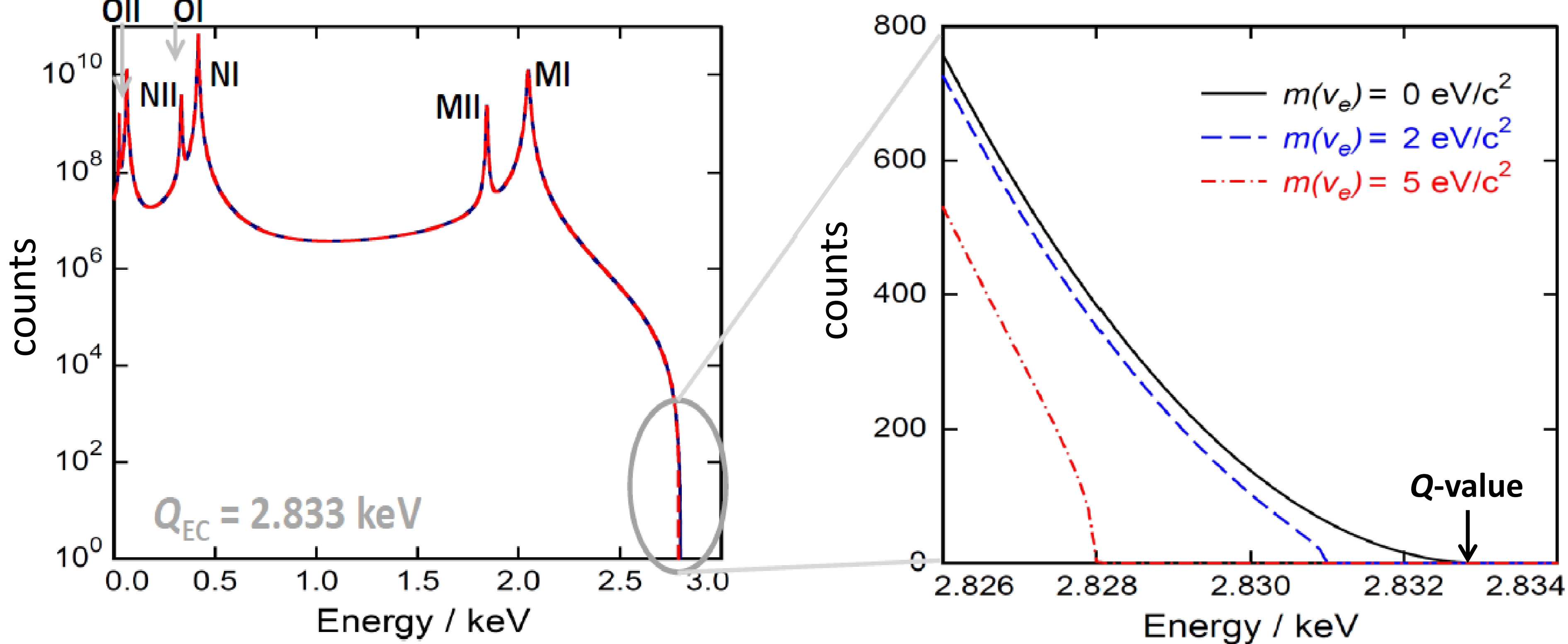
A. De Rujula, M. Lusignoli, Phys. Lett. B **118** (1982) 429

$$^{163}_{67}\mathrm{Ho} \;\rightarrow\; ^{163}_{66}\mathrm{Dy}^* + \nu_e$$
$$\hookrightarrow\; ^{163}_{66}\mathrm{Dy} + E_C$$

$p + e^- \;\rightarrow\; n + \nu_e$



“The Electron Capture in ^{163}Ho experiment – ECHo“ by L. Gastaldo, 12:00, Tuesday 3

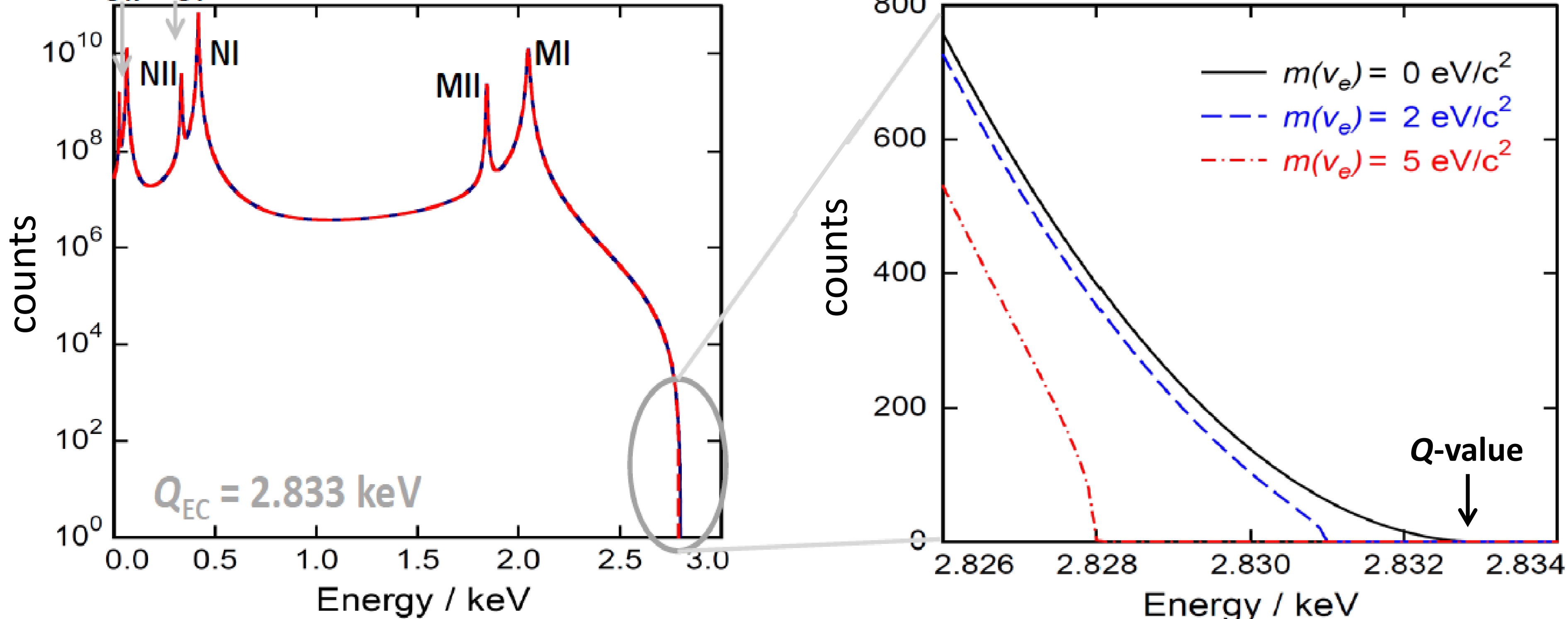


$$\frac{dN}{dE} = A(Q - E)^2 \sqrt{1 - \frac{m_\nu^2}{(Q-E)^2}} \sum C\phi_k^2(0) \frac{\Gamma_k/2\pi}{(E - B_k)^2 + \Gamma_k^2/4}$$

Underlying technique – cryogenic microcalorimetry

L. Gastaldo et al., J. Low Temp. Phys. 176 (2014) 876

P.C.-O. Ranitzsch et al., J. Low Temp. Phys. 167 (2012) 1004



$$\frac{dN}{dE} = A(Q - E)^2 \sqrt{1 - \frac{m_\nu^2}{(Q-E)^2}} \sum C\phi_k^2(0) \frac{\Gamma_k/_{2\pi}}{(E - B_k)^2 + \Gamma_k^2/_4}$$

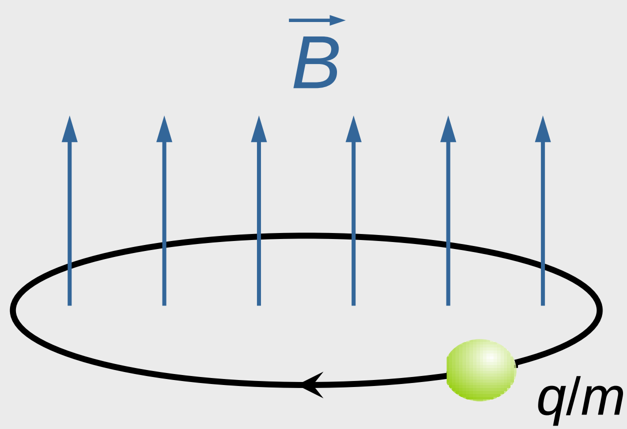
Q microcalorimetry $\xleftrightarrow{\text{comparison}}$ *Q* from PENTATRAP

$\delta Q \approx 1$ eV

Systematic uncertainty in determination of m_ν

Penning trap

(the most accurate mass spectrometer !!!)



$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

- Mass $\longleftarrow$ Frequency
- Magnetic field of a few Tesla
- Homogeniety of B-field: $10^{-7}/cm^3$
- Trapping volume: a few microns^3
- High temporal stability of B-field

$\Downarrow$

uncertainty of **< 10^{-11}**
in ***mass-ratio*** determination

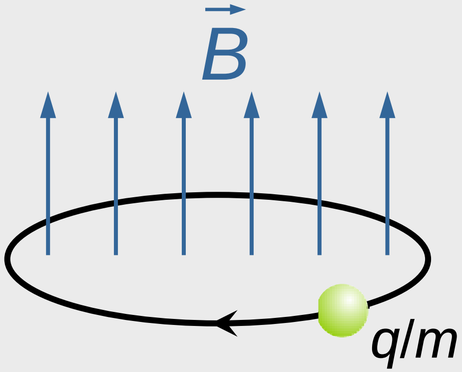
$$Q = M_p - M_d = M_d \cdot \left(\frac{M_p}{M_d} - 1\right)$$

PENTATRAP

Max-Planck Institute for Nuclear Physics, Heidelberg

$$\frac{\Delta B}{B} < 5 \cdot 10^{-10}\ h^{-1}$$

strong uniform static B-field



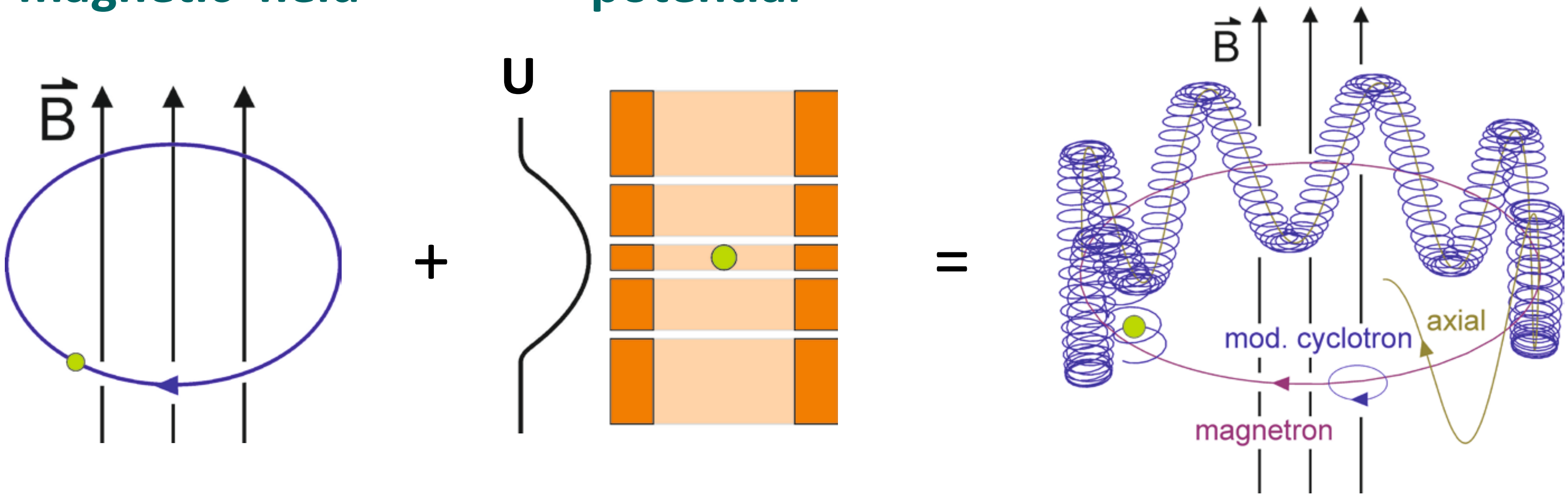
$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

THe-TRAP

Max-Planck Institute for Nuclear Physics, Heidelberg

$$\frac{\Delta B}{B} < 10^{-11}\ h^{-1}$$

strong uniform magnetic field | **harmonic electrical potential** | **3 eigenmotions in trap**



cyclotron motion:

$$\nu_+ = \nu_c \cdot \left(\frac{1}{2} + \frac{1}{2}\sqrt{1 - 2\nu_z^2} \right)$$

magnetron motion:

$$\nu_- = \nu_c \cdot \left(\frac{1}{2} - \frac{1}{2}\sqrt{1 - 2\nu_z^2} \right)$$

axial motion:

$$\nu_z = \frac{1}{2\pi}\sqrt{\frac{q}{m} \cdot \frac{U}{d^2}}$$

$$\nu_c^2 = \nu_+^2 + \nu_-^2 + \nu_z^2 \qquad \frac{\delta\nu_c}{\nu_c} < 10^{-10}$$

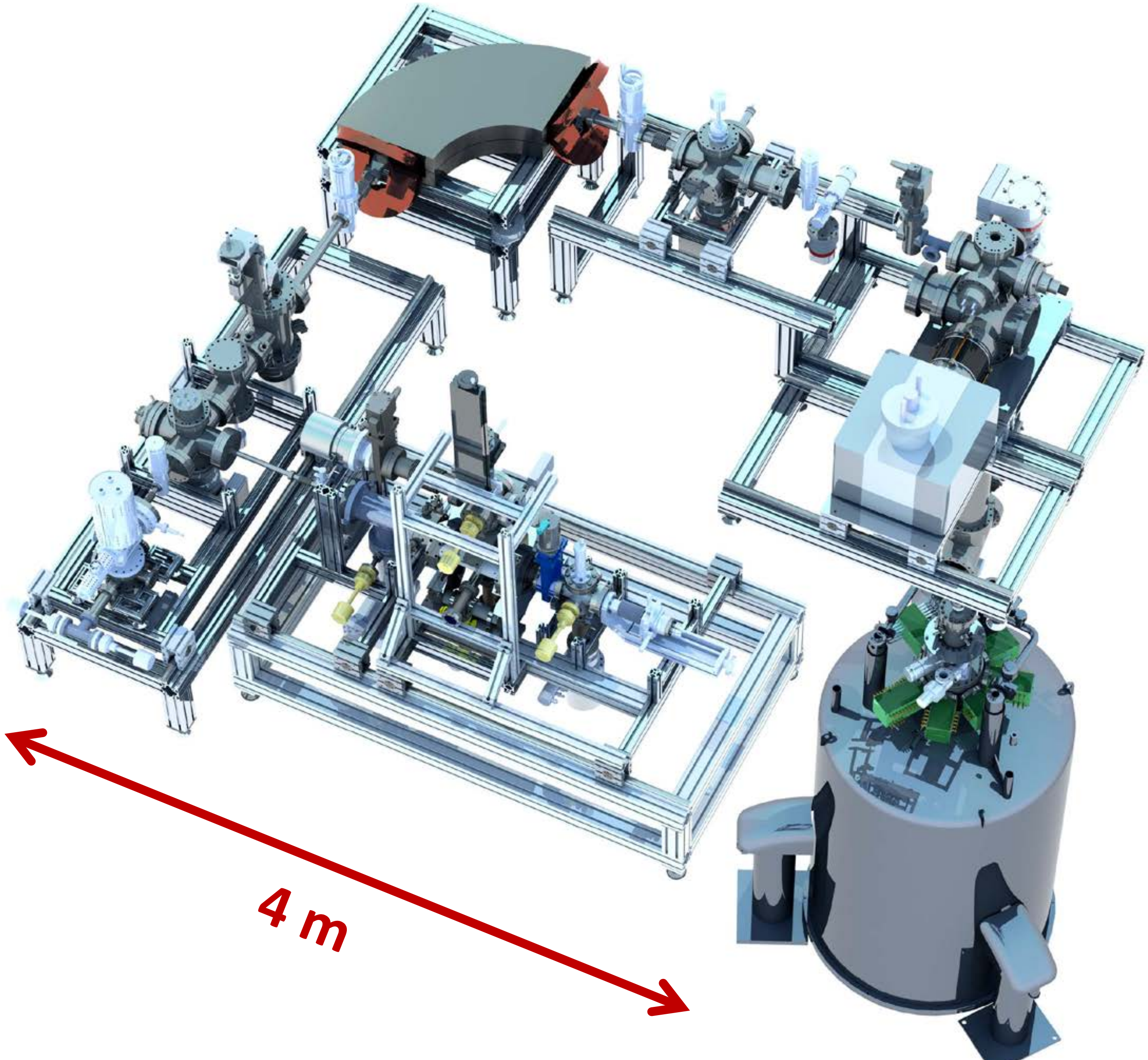
long-lived and stable nuclides

$$\nu_c = \nu_+ + \nu_- \qquad \frac{\delta\nu_c}{\nu_c} > 10^{-10}$$

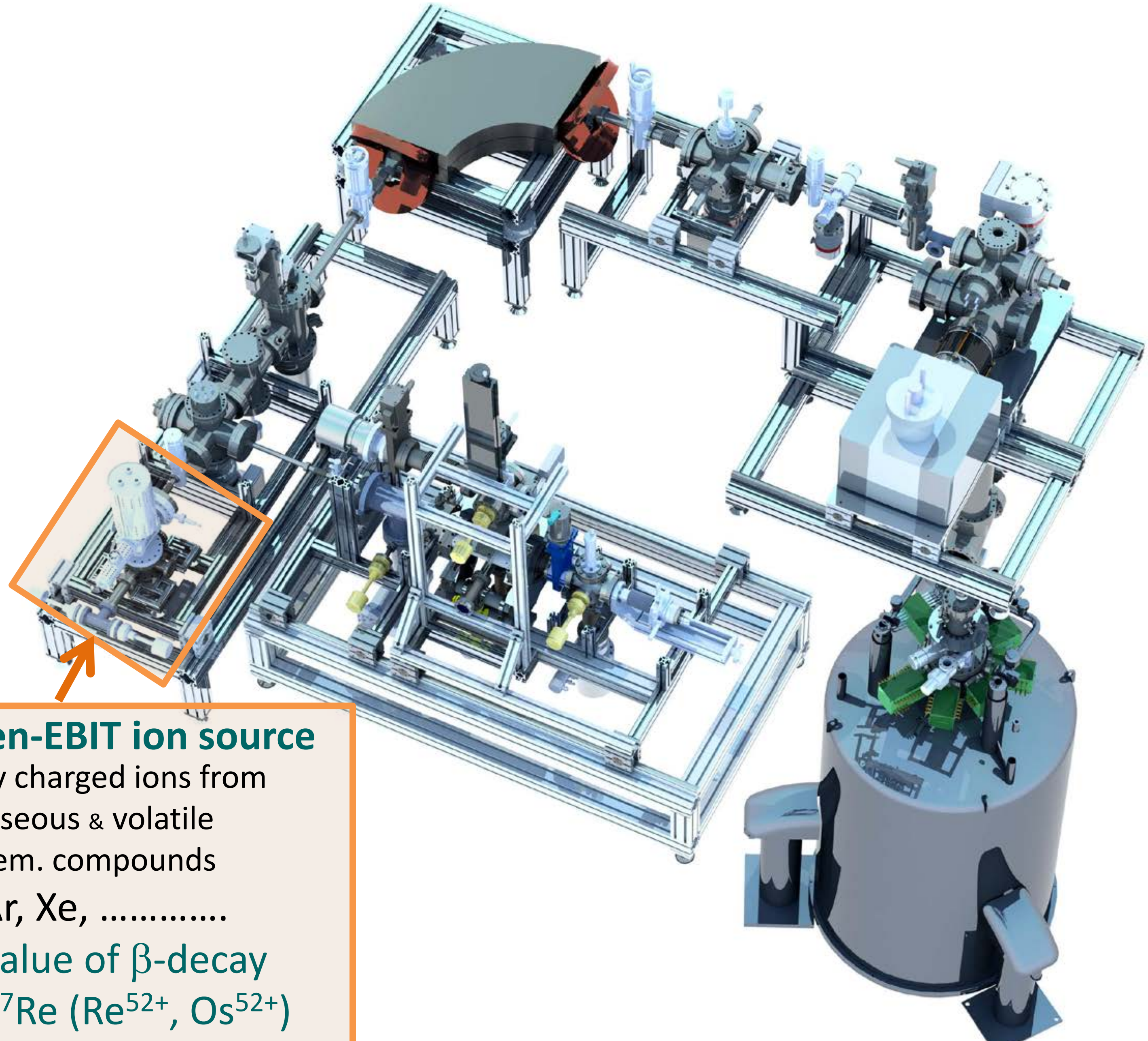
short-lived nuclides

Rev. Mod. Phys. 58, 233 (1986).

PENTATRAP setup

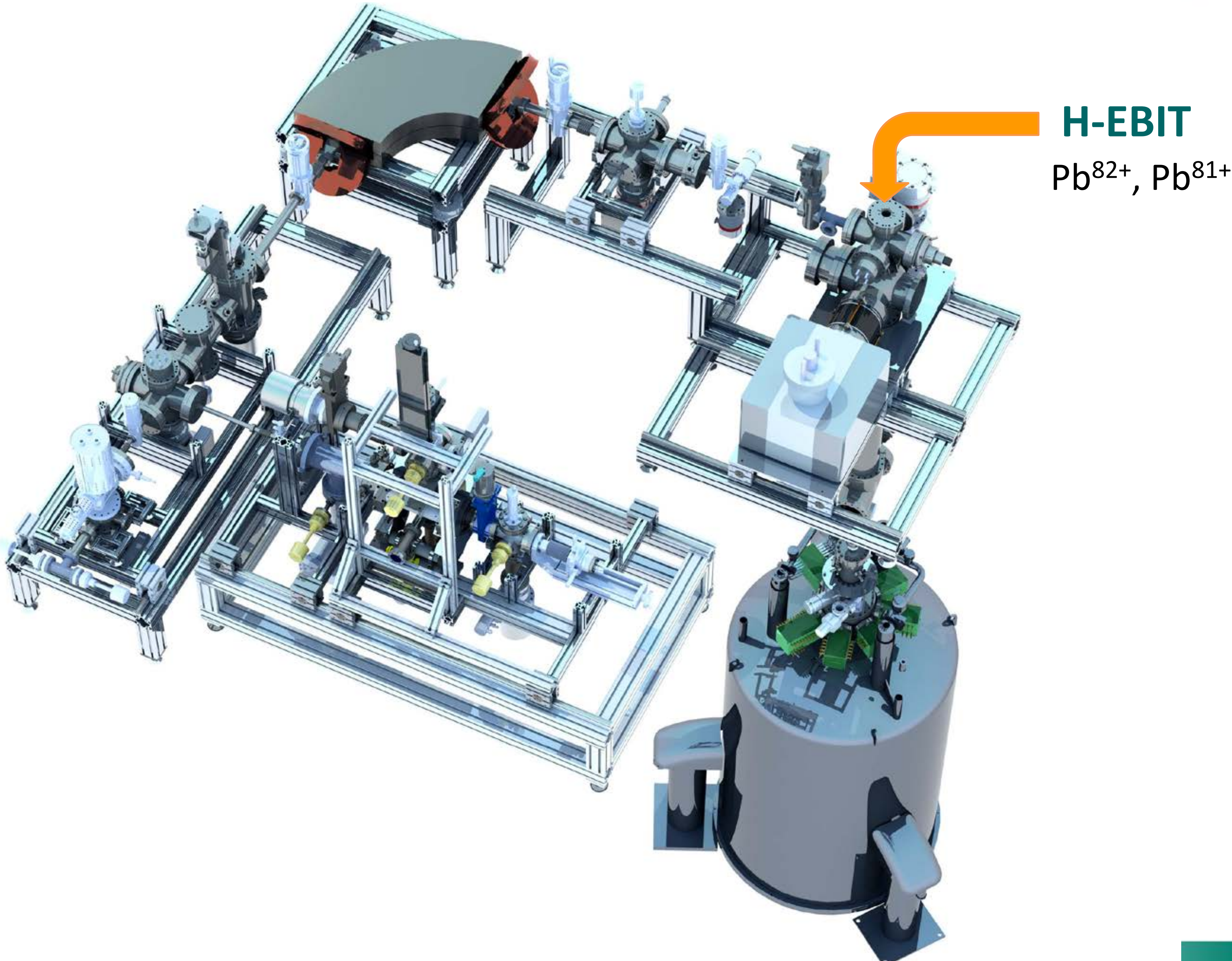


PENTATRAP setup

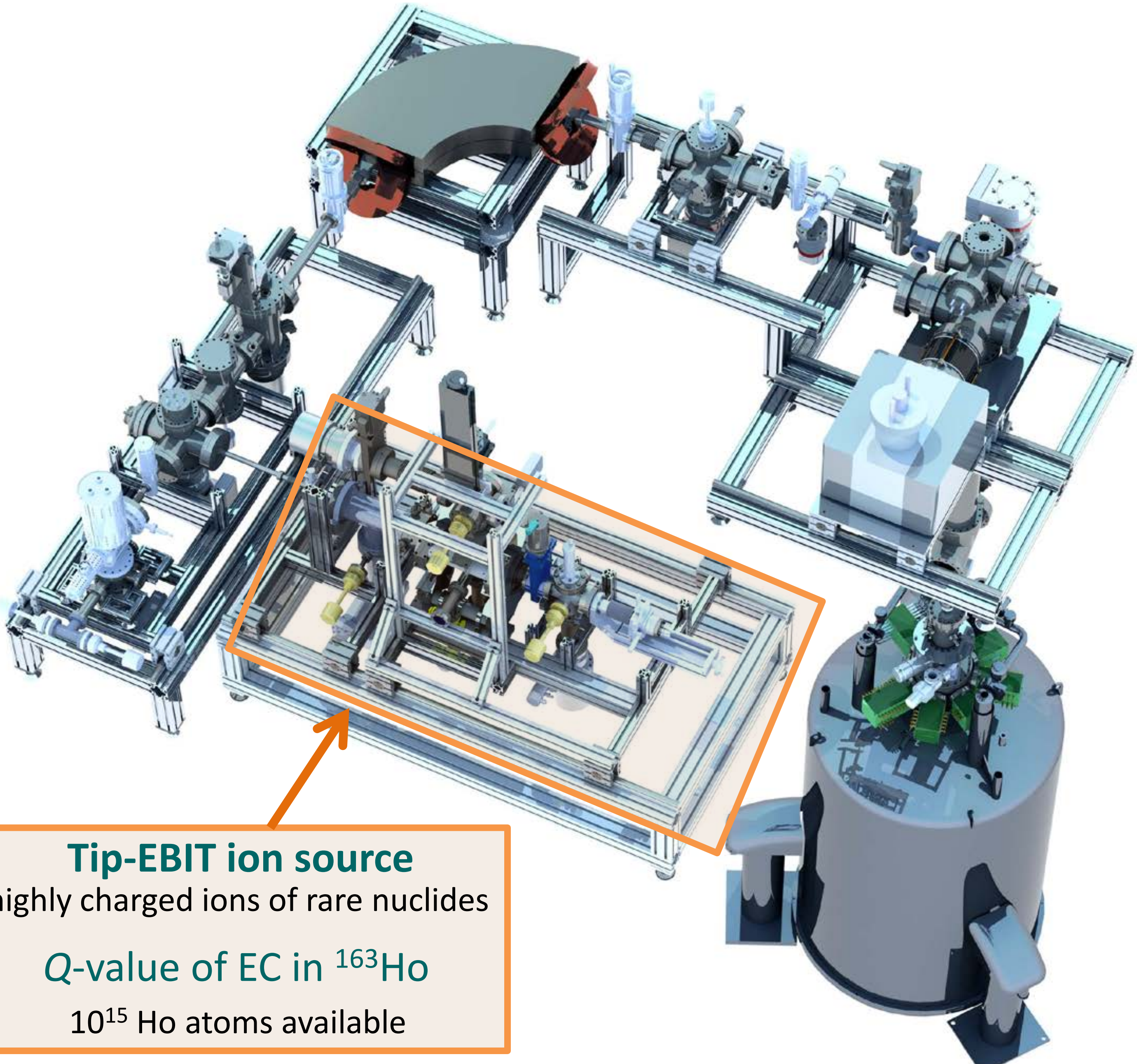


Dresden-EBIT ion source
highly charged ions from
gaseous & volatile
chem. compounds
Ar, Xe, ...
Q-value of β-decay
of ^{187}Re (Re^{52+}, Os^{52+})

PENTATRAP setup



PENTATRAP setup

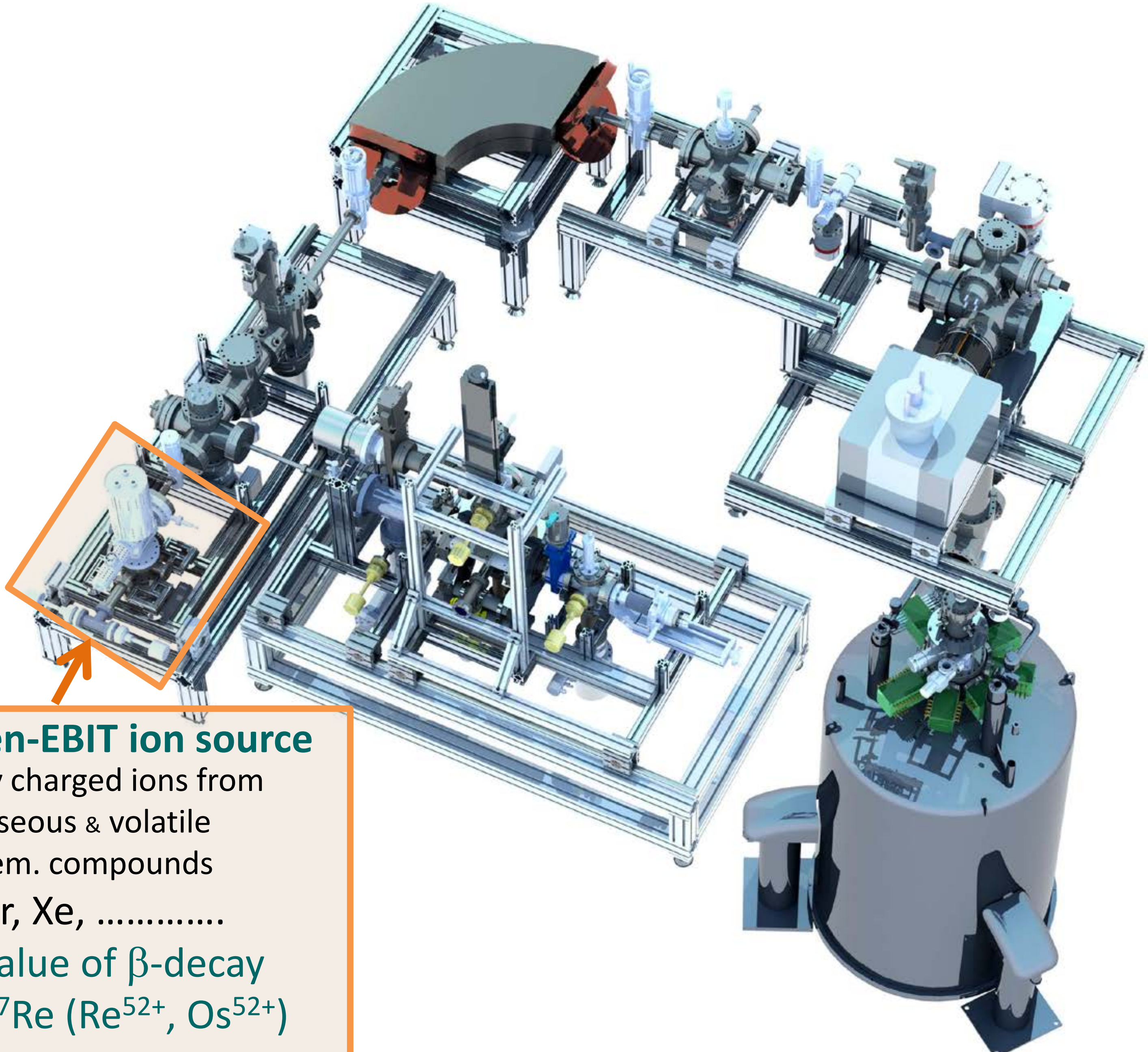


Tip-EBIT ion source
highly charged ions of rare nuclides

Q-value of EC in ^{163}Ho

10^{15} Ho atoms available

PENTATRAP setup



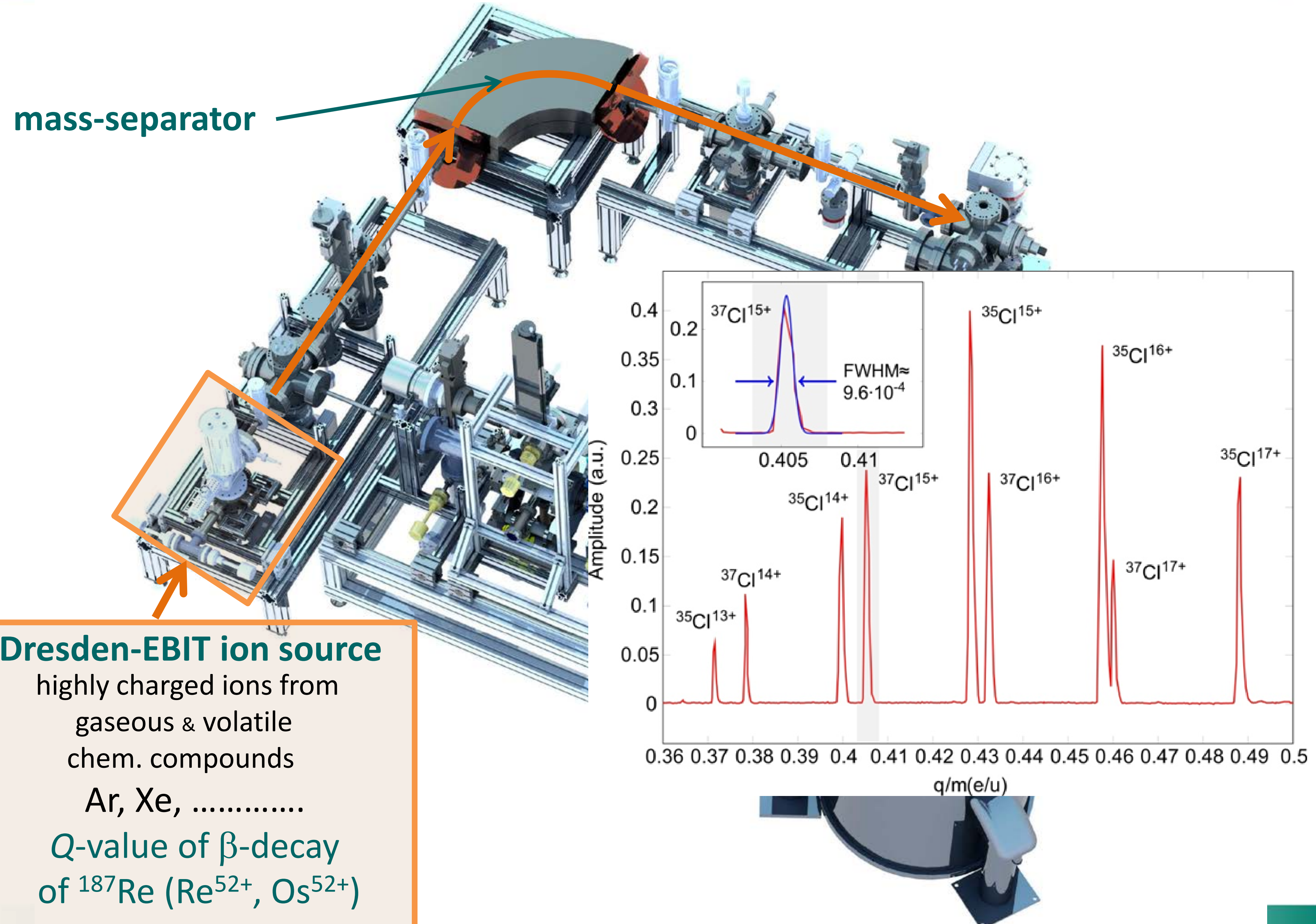
Dresden-EBIT ion source

highly charged ions from
gaseous & volatile
chem. compounds

Ar, Xe, ...

Q-value of β-decay
of ^{187}Re (Re^{52+}, Os^{52+})

PENTATRAP setup



Dresden-EBIT ion source

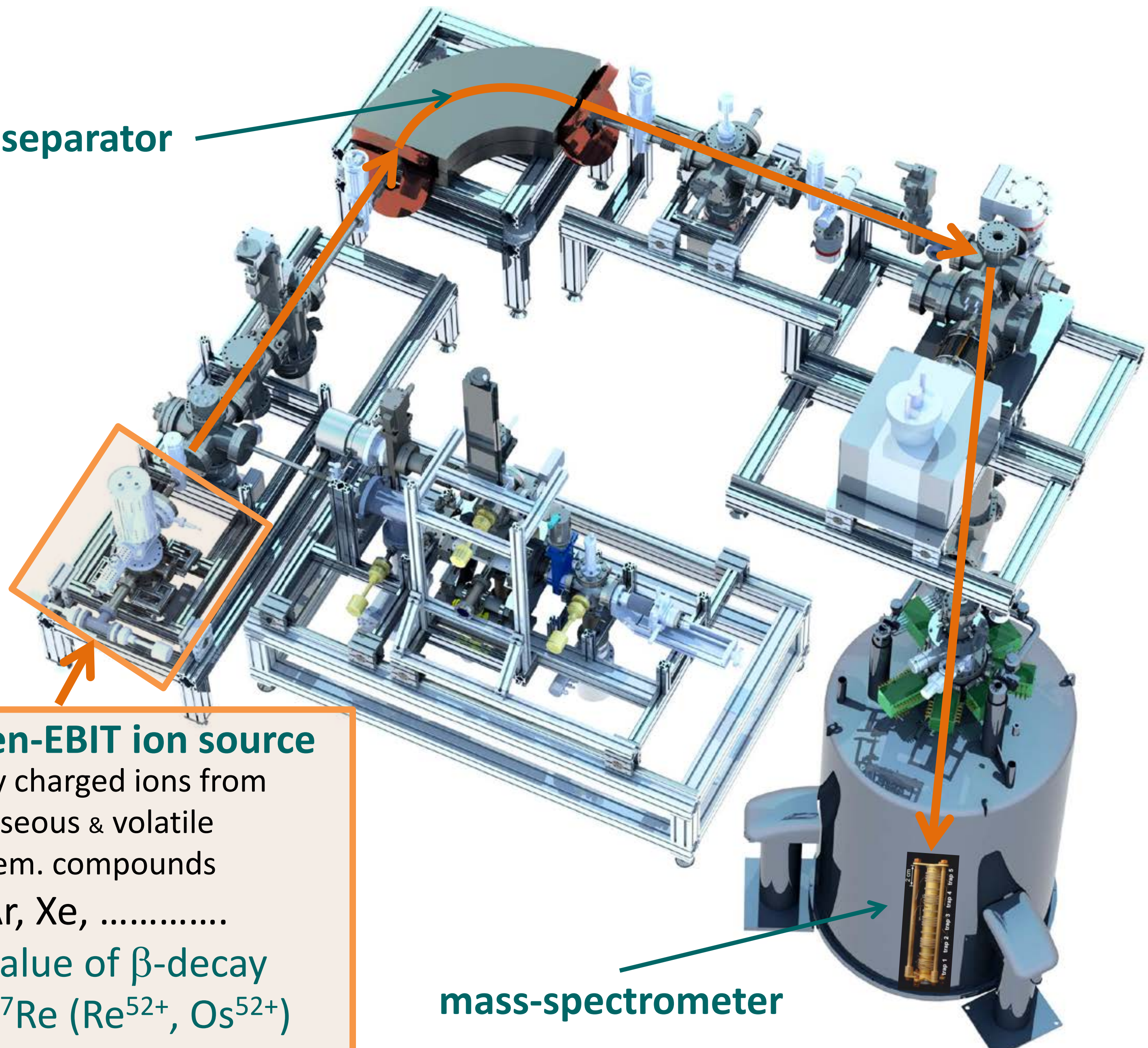
highly charged ions from
gaseous & volatile
chem. compounds

Ar, Xe, ...

Q-value of β-decay
of ^{187}Re (Re^{52+}, Os^{52+})

PENTATRAP setup

mass-separator



Dresden-EBIT ion source

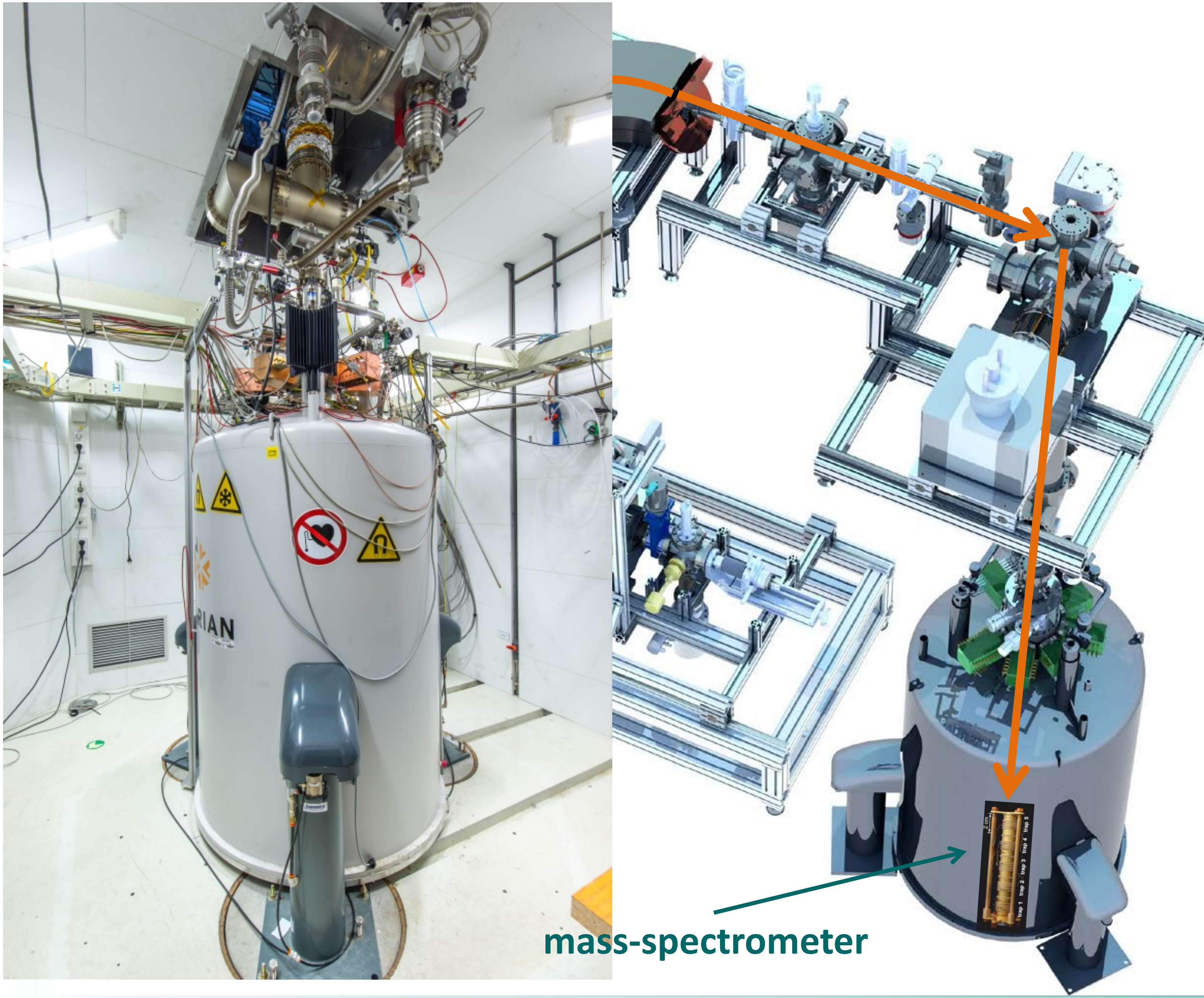
highly charged ions from
gaseous & volatile
chem. compounds

Ar, Xe, ...

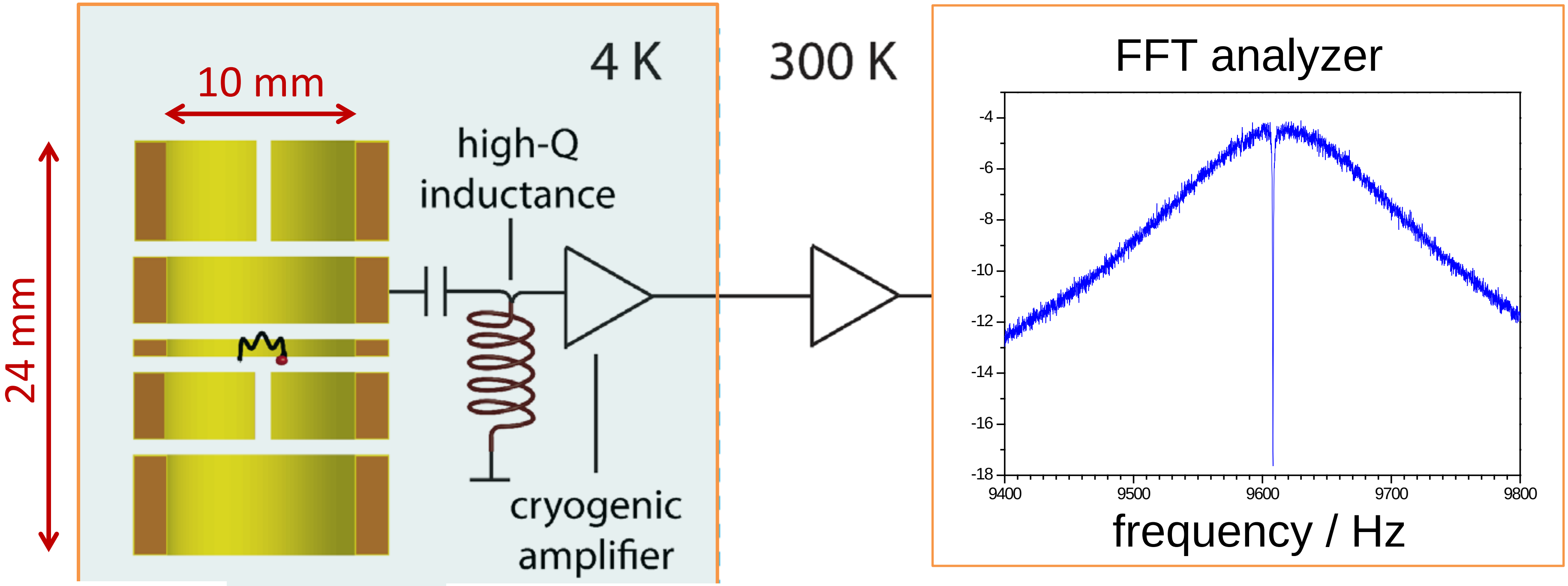
Q-value of β-decay
of ^{187}Re (Re^{52+}, Os^{52+})

mass-spectrometer

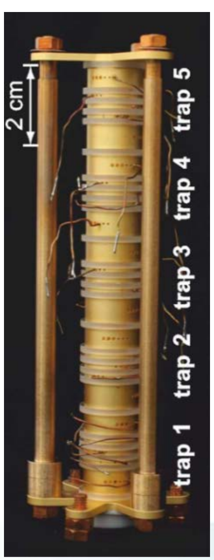
PENTATRAP setup



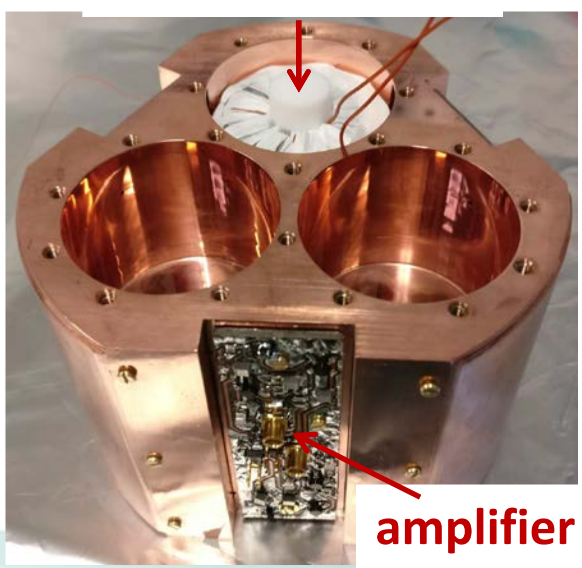
Measurement of trap frequencies with PENTATRAP



trap tower



NbTi toroidal coil



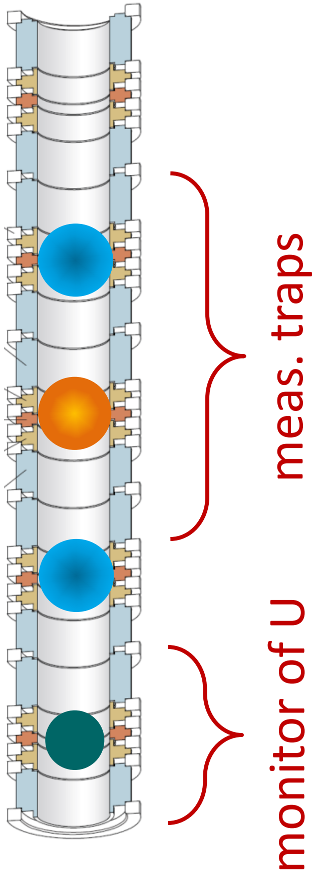
axial motion: $\rho_z \sim 10\ \mu m$

cyclotron motion: $\rho_+ \sim 1\ \mu m$

magnetron motion: $\rho_- \sim 1\ \mu m$

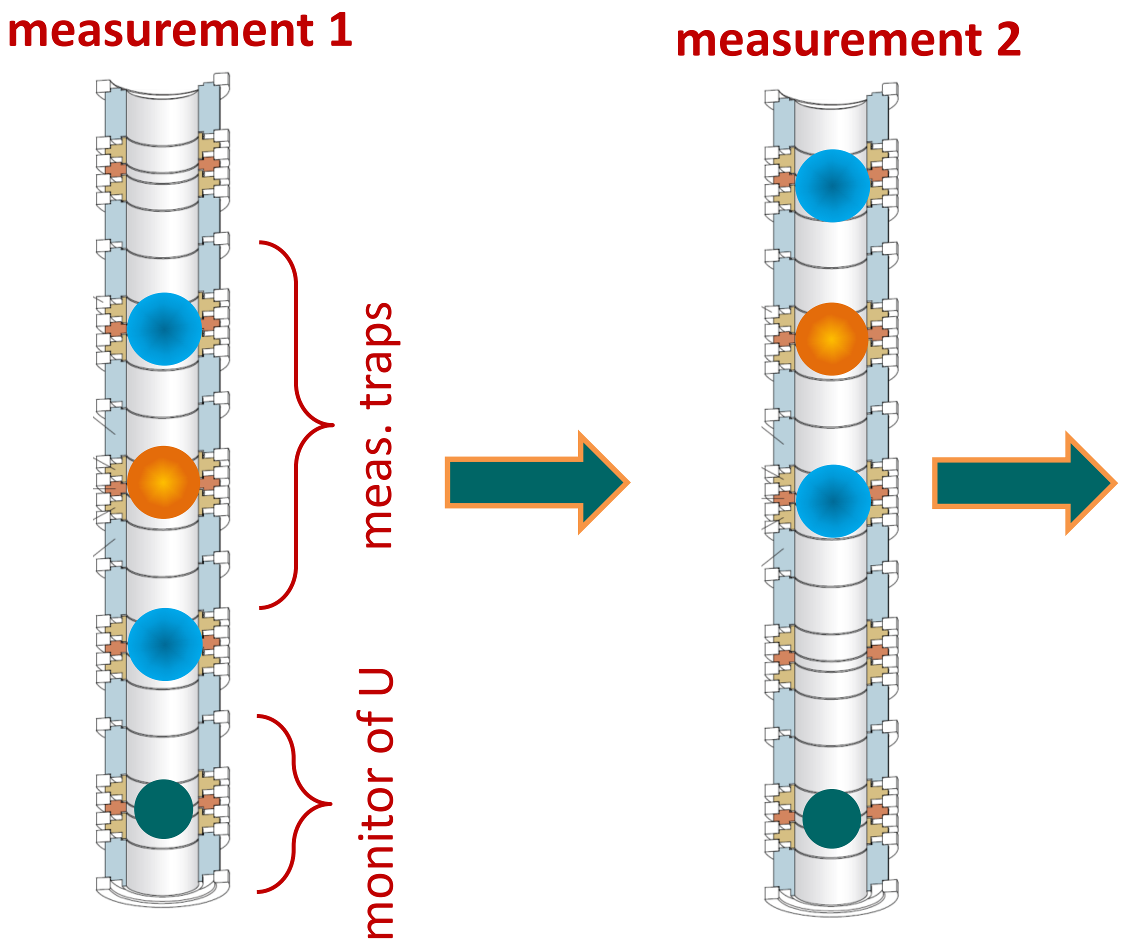
stability of B-field and trap electric potential

measurement 1



$$R(t_1) = \frac{\nu_1(t_1)}{\nu_2(t_1)} = \frac{m_2}{m_1}\,\frac{B_2(t_1)}{B_1(t_1)}$$

stability of B-field and trap electric potential



$$\sqrt{R(t_1)R(t_2)} = \frac{m_2}{m_1}$$

$$\frac{B_1}{B_2} \approx \text{Const}$$

$$R(t_1) = \frac{\nu_1(t_1)}{\nu_2(t_1)} = \frac{m_2}{m_1}\,\frac{B_2(t_1)}{B_1(t_1)}$$

$$R(t_2) = \frac{\nu_1(t_2)}{\nu_2(t_2)} = \frac{m_2}{m_1}\,\frac{B_1(t_2)}{B_2(t_2)}$$

Commissioning of PENTATRAP: April 2018

mass ratios with an uncertainties:

$5 \cdot 10^{-11} - 1 \cdot 10^{-10}$

Mass Difference	Result (u)
$^{84}Kr - ^{83}Kr$	0.997 371 212 7(86)(23)(89)
$^{84}Kr - ^{82}Kr$	1.998 016 573 2(46)(22)(51)
$^{86}Kr - ^{82}Kr$	3.997 129 467 8(80)(49)(94)
$^{131}Xe - ^{129}Xe$	2.000 303 279 2(85)(43)(95)
$^{132}Xe - ^{131}Xe$	0.999 070 949 6(134)(51)(144)
$^{134}Xe - ^{132}Xe$	2.001 237 945 6(79)(32)(85)

M. Hoecker, R. Rana and Ed.G. Myers, Phys. Rev. A 88 (2013) 052502

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M. Hoecker, R. Rana and Ed.G. Myers, Phys. Rev. A 88 (2013) 052502

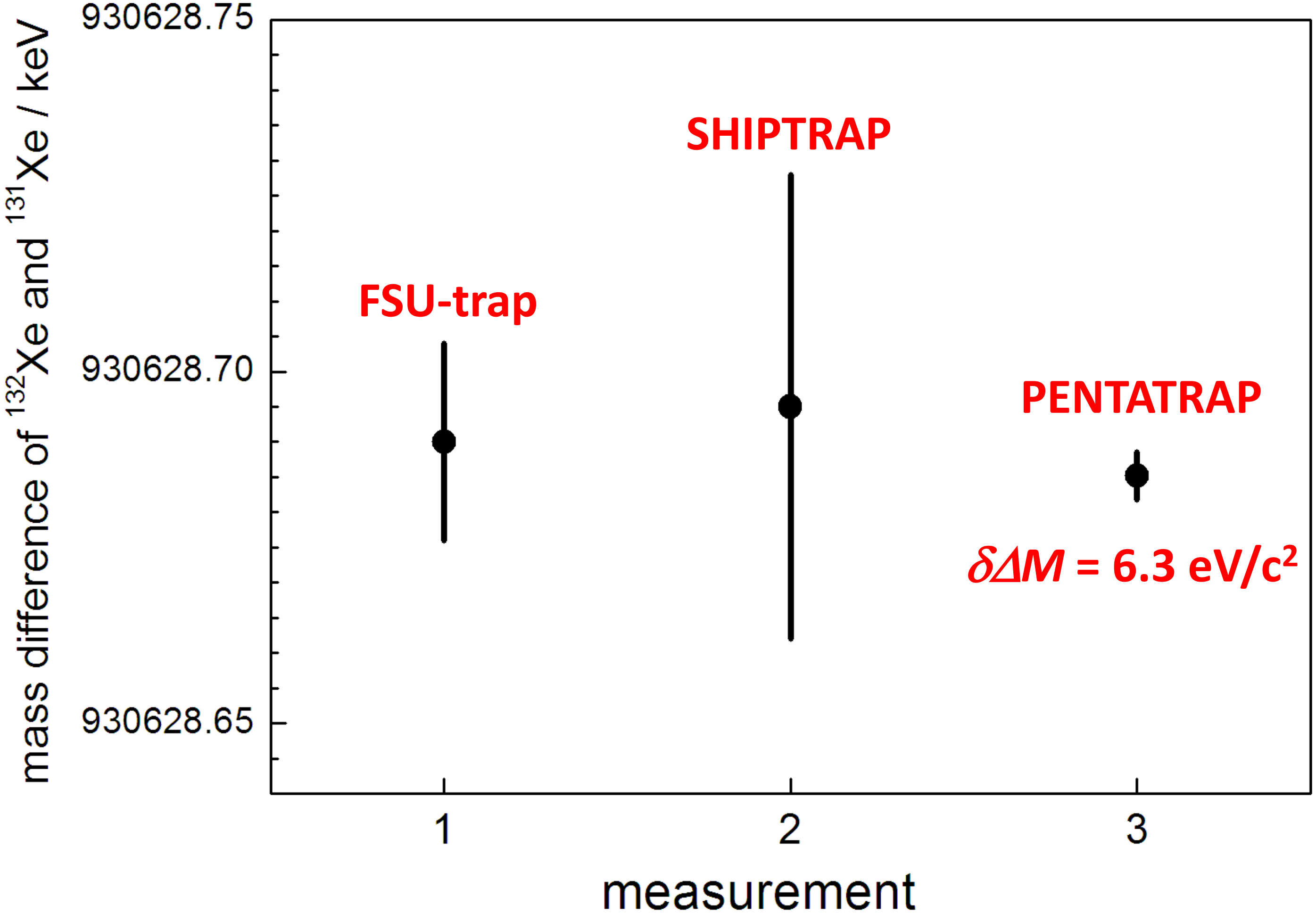
$R = m(^{132}Xe^{17+})/\, m(^{131}Xe^{17+}) = 1.007632569093 \pm 2.2E\text{-}11$

in agreement with the FSU-trap value

Final frequency ratio (16 groups of 2-hour measurements each):

$$R = m(^{132}Xe^{17+})/\, m(^{131}Xe^{17+}) = 1.007632569093 \pm 2.2E\text{-}11$$

in agreement with the FSU-trap value



Commissioning of PENTATRAP: to come soon

Mass Difference	Result (u)
$^{84}Kr - ^{83}Kr$	0.997 371 212 7(86)(23)(89)
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M. Hoecker, R. Rana and Ed.G. Myers, Phys. Rev. A 88 (2013) 052502

mass ratio with an uncertainty of ~ $3 \cdot 10^{-11}$

Binding Energy of 18th electron in Xe: $M(^{132}Xe^{18+}) - M(^{132}Xe^{17+})$

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Atomic Data and Nuclear Data Tables 86 (2004) 117–233

Atomic Data AND Nuclear Data Tables

www.elsevier.com/locate/adt

Systematic calculation of total atomic energies of ground state configurations☆

G.C. Rodrigues,[a,1] P. Indelicato,[a] J.P. Santos,[b,c,*] P. Patté,[c] and F. Parente,[c,d]

[a] *Laboratoire Kastler-Brossel, École Normale Supérieure et Université Pierre et Marie Curie, Case 74, 4 place Jussieu, F-75252 Paris Cedex 05, France*
[b] *Departamento de Física, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Monte de Caparica, 2825-114 Caparica, Portugal*
[c] *Centro de Física Atómica da Universidade de Lisboa, Av. Prof. Gama Pinto 2, 1649-003 Lisboa, Portugal*
[d] *Departamento Física da Universidade de Lisboa, Portugal*

$B^{18th\_e}(Xe)\Big| = 434$ eV

P. Indelicato: 432.4(0.5) eV

↓

$$\delta[M(^{132}Xe^{18+})/M(^{132}Xe^{17+})] \approx 4 \cdot 10^{-12}$$

Binding Energy of 18th electron in Xe: $M(^{132}Xe^{18+}) - M(^{132}Xe^{17+})$

$B^{18th\_e}(Xe)\Big|$ = 434 eV

$B^{18th\_e}(Xe)\Big|_{\text{P. Indelicato}}$ = 432.4(0.5) eV

Measurement with PENTATRAP

$$\delta[M(^{132}Xe^{18+})/M(^{132}Xe^{17+})] \approx \begin{matrix} 1.1 \cdot 10^{-11}\ \text{(stat)} \\ 2.0 \cdot 10^{-11}\ \text{(sys)} \end{matrix}$$

$$B^{18th\_e}(Xe)\Big|_{\text{PENTATRAP}} = 433.0(3.0)\ \text{eV}$$

(2) "warmup" measurement

Q-value of **β-decay of ^{187}Re** with ~ **a few eV** uncertainty

Q_{Re}= 2466.7(1.5) eV (MARE project)

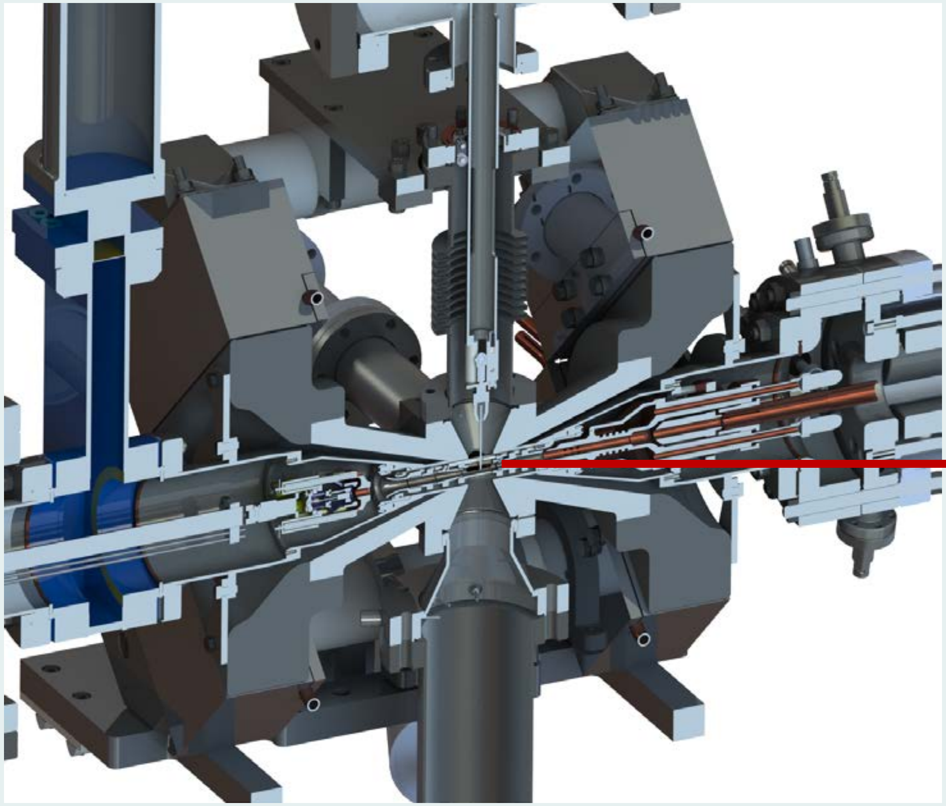
(3) first physics case

Q-value of **EC in ^{163}Ho** with ~ **a few eV** uncertainty

a dedicated source of highly charged ^{163}Ho ions is required

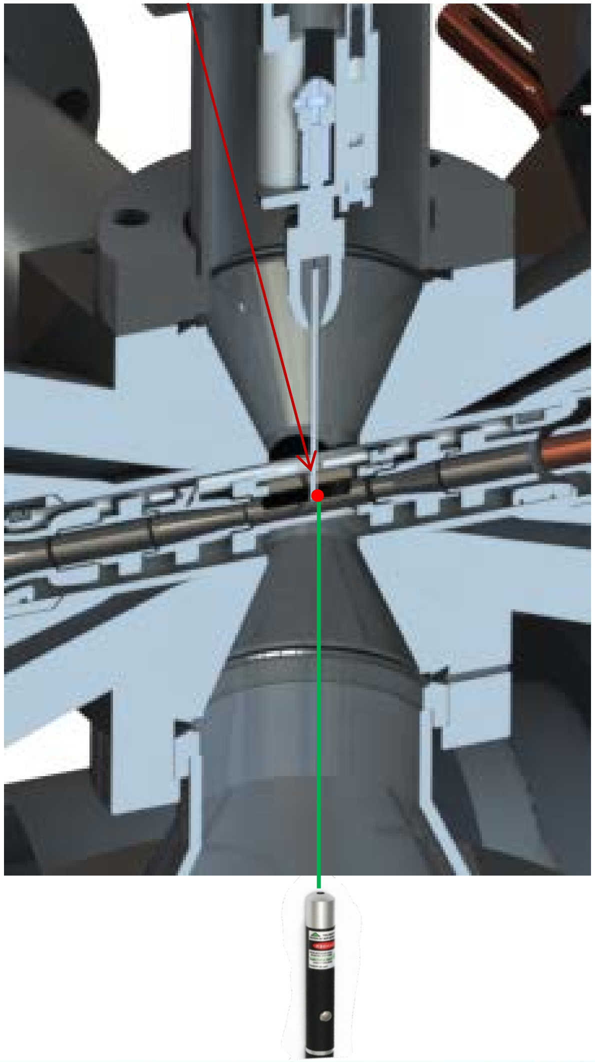
Highly Charged ^{163}Ho Ions – TIP EBIT

Mini-EBIT developed in Crespo's group

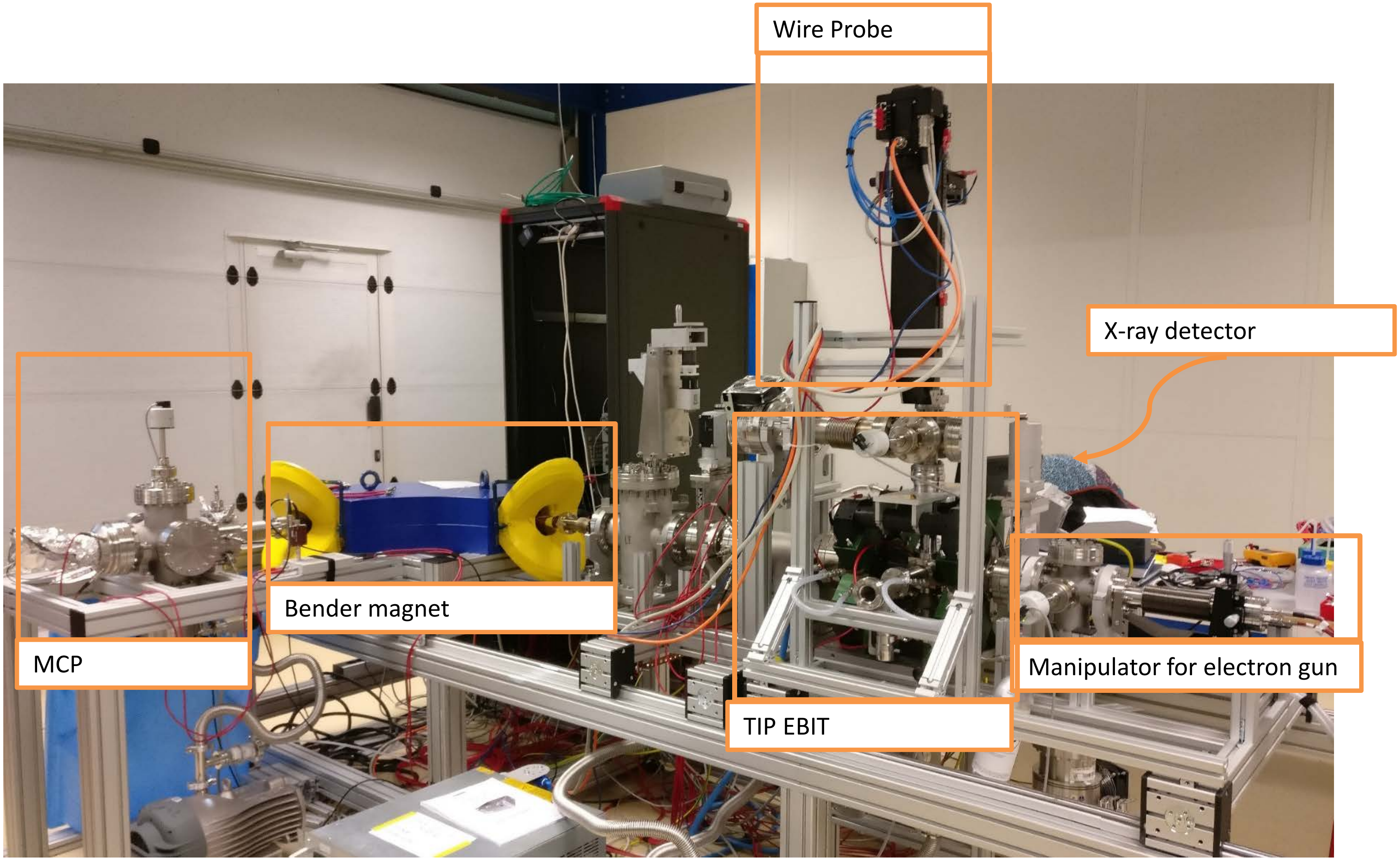


compact room temperature
permanent magnet, 0.8 T
max. electron current = 60 mA

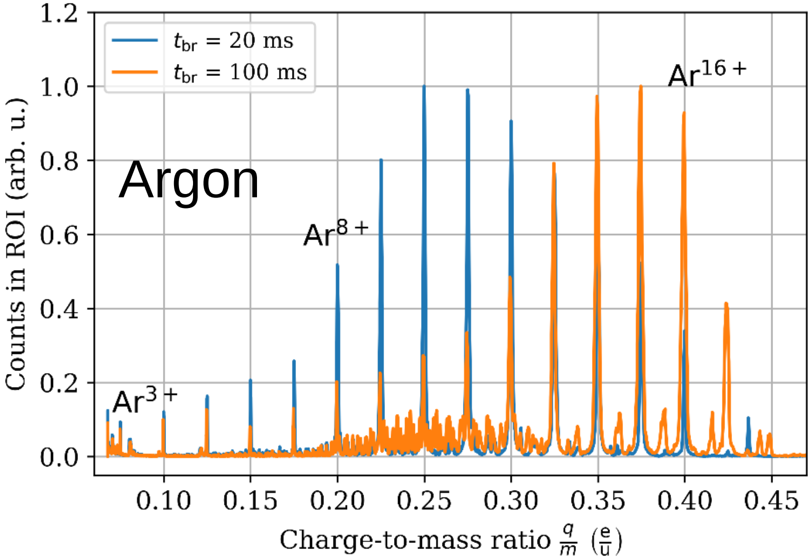
Rima Schüssler
Christoph Schweiger

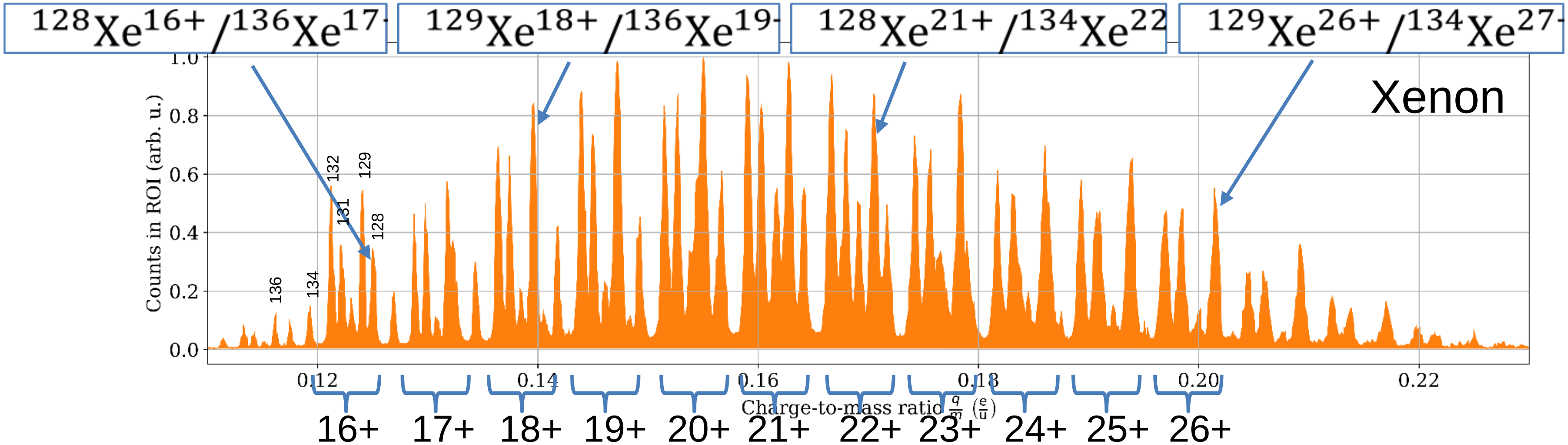


Highly Charged ^{163}Ho Ions – TIP-EBIT



Commissioning of TIP-EBIT: Extraction





(1) 2018-2019

Q-value of **β-decay of ^{187}Re**
with **a few eV** uncertainty

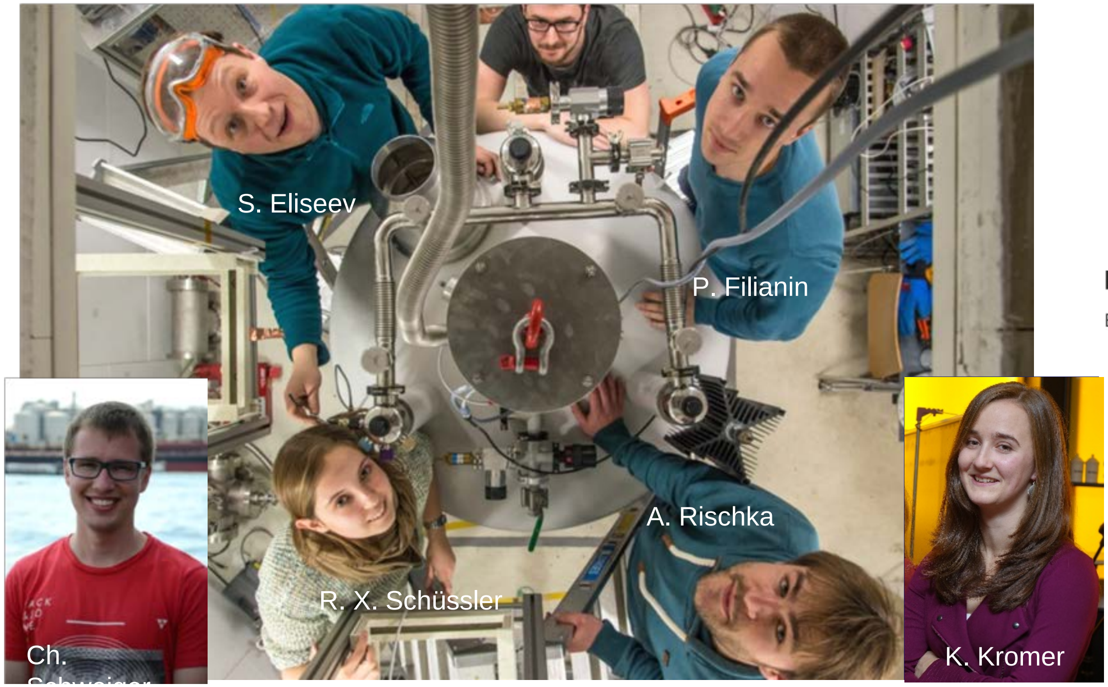
(2) 2019-2020

Q-value of **electron capture in ^{163}Ho**
with **a few eV** uncertainty

European Research Council

Established by the European Commission

ERC Grant No. 290870 - MEFUCO

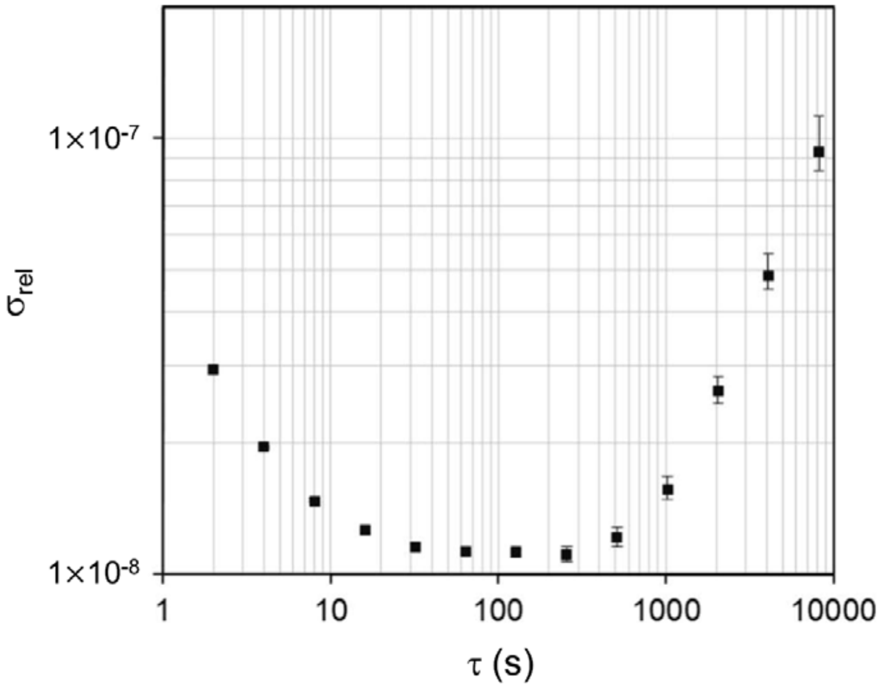


DFG Research Unit FOR 2202

Collaboration members: Alexander Rischka, Rima X. Schüssler, Christoph Schweiger, Pavel Filianin, Kathrin Kromer, Sergey Eliseev, Yuri N. Novikov, Sven Sturm, Hendrik Bekker, Peter Micke, José R. Crespo López-Urrutia, Stefan Ulmer, Klaus Blaum

Thank you for your attention !

StaRep – Ultra stable voltage source

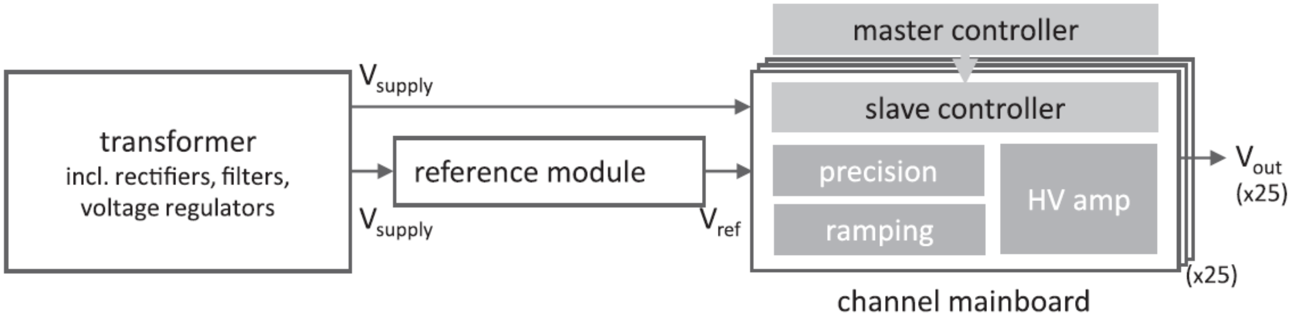


Voltage range: 0 V to -100 V

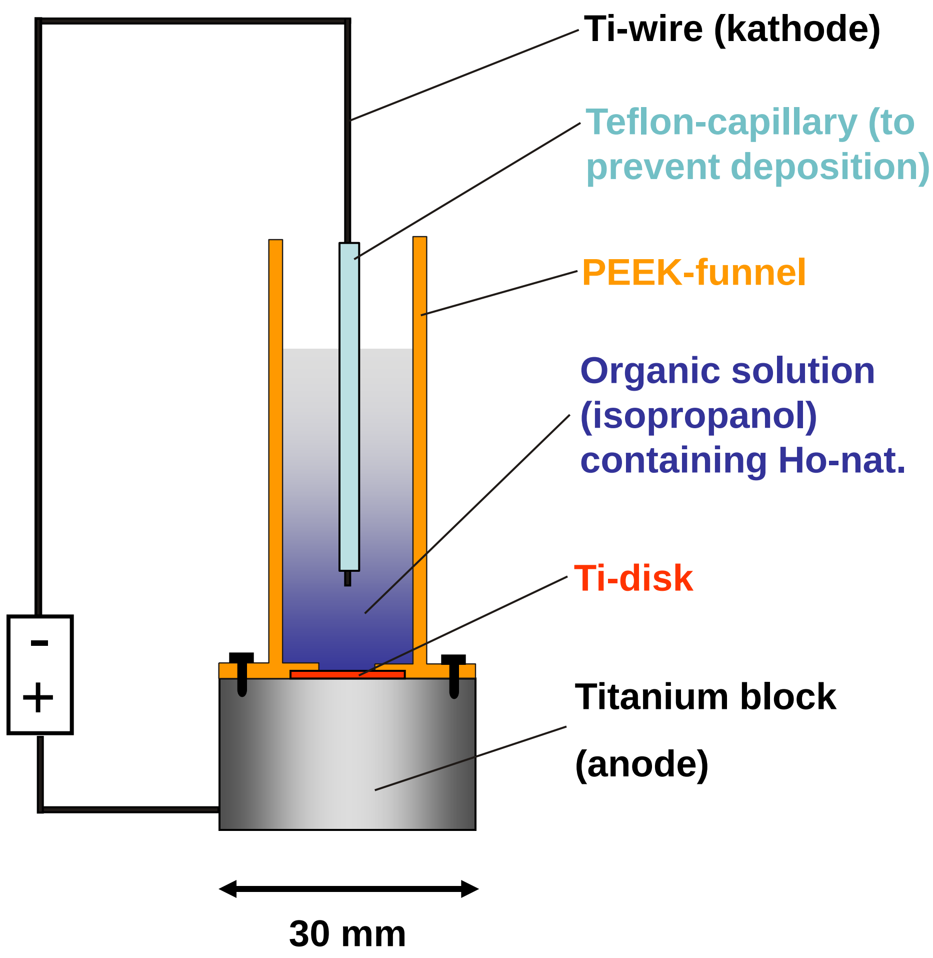
Rel. stability: < 10E-8 @ 10 min

Noise (0.1 Hz – 10 Hz): < 1.5 µV

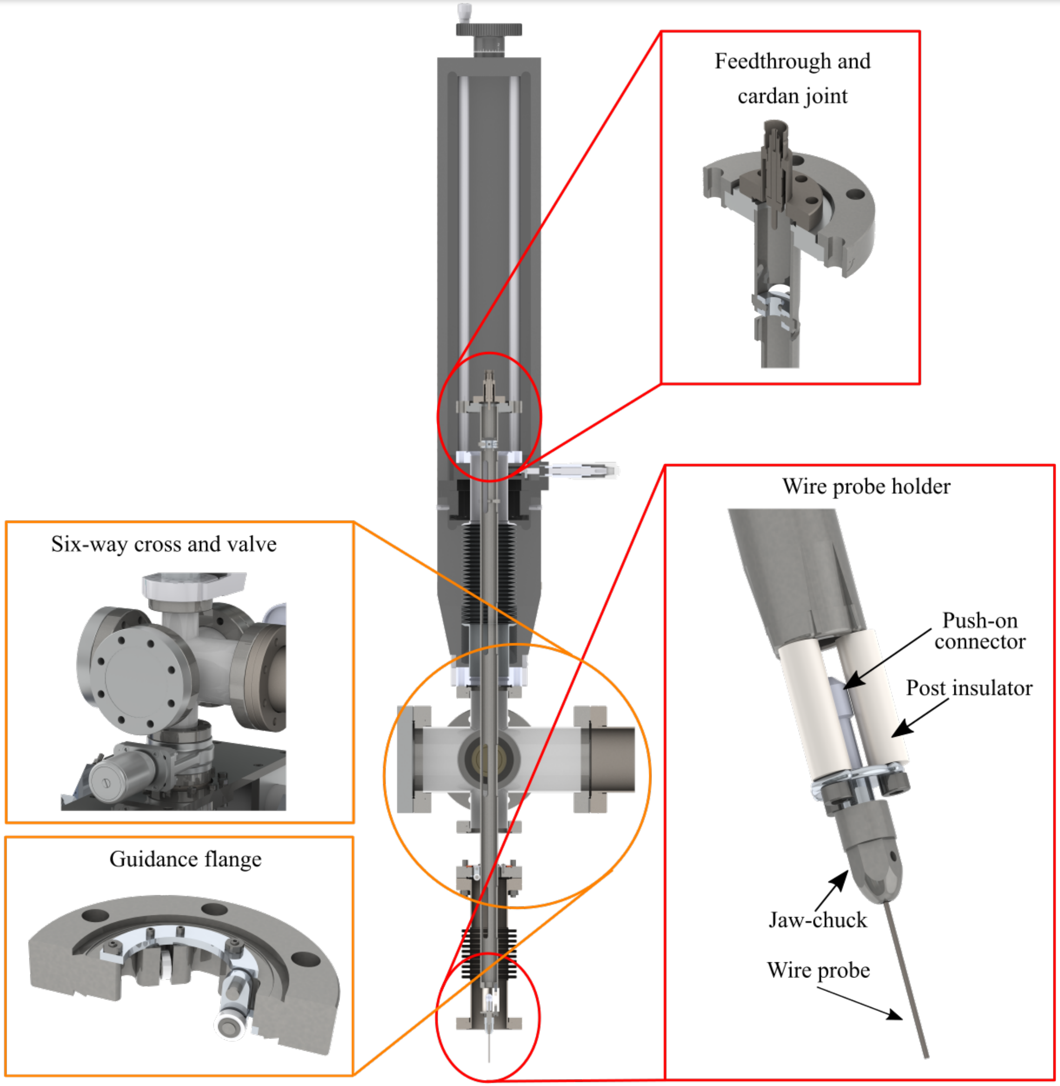
Temp. coeff. < 0.1 ppm/K



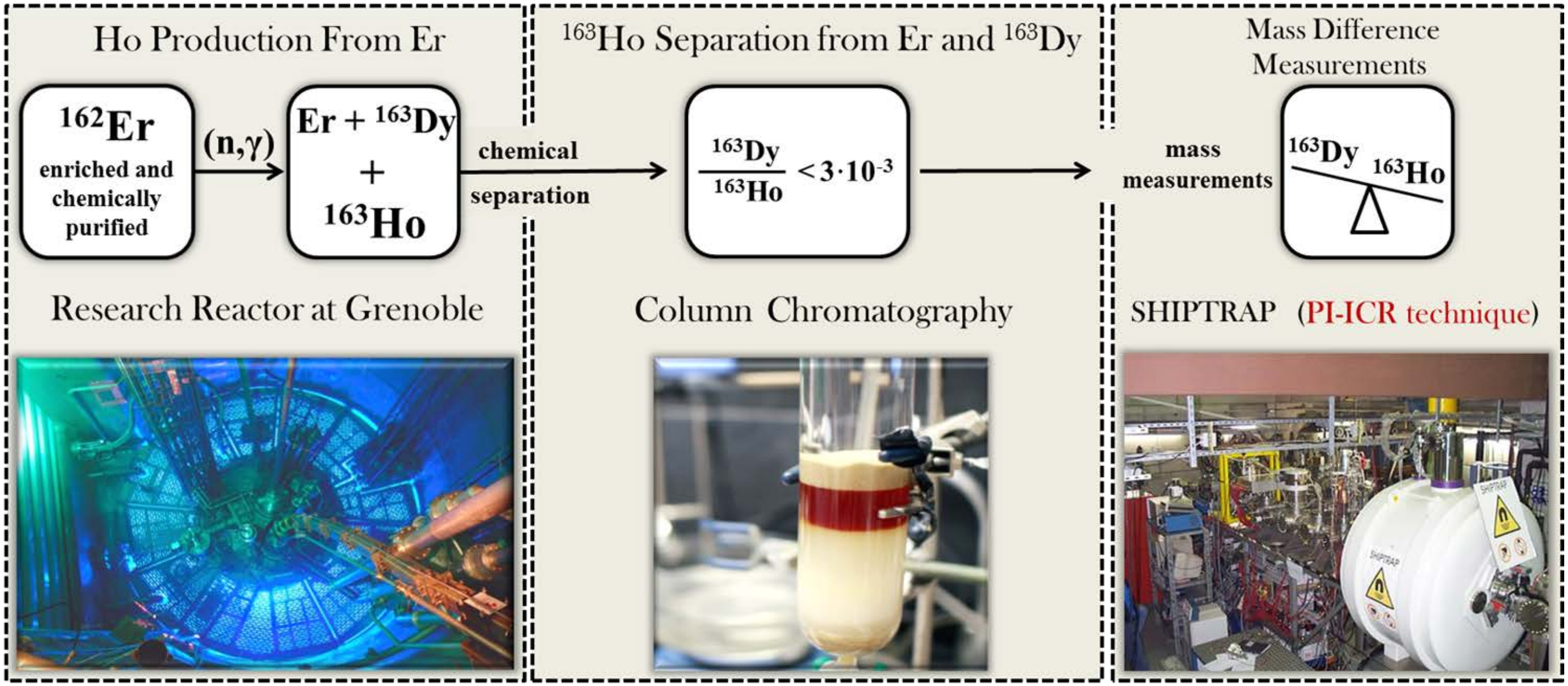
^{163}Ho wire preparation

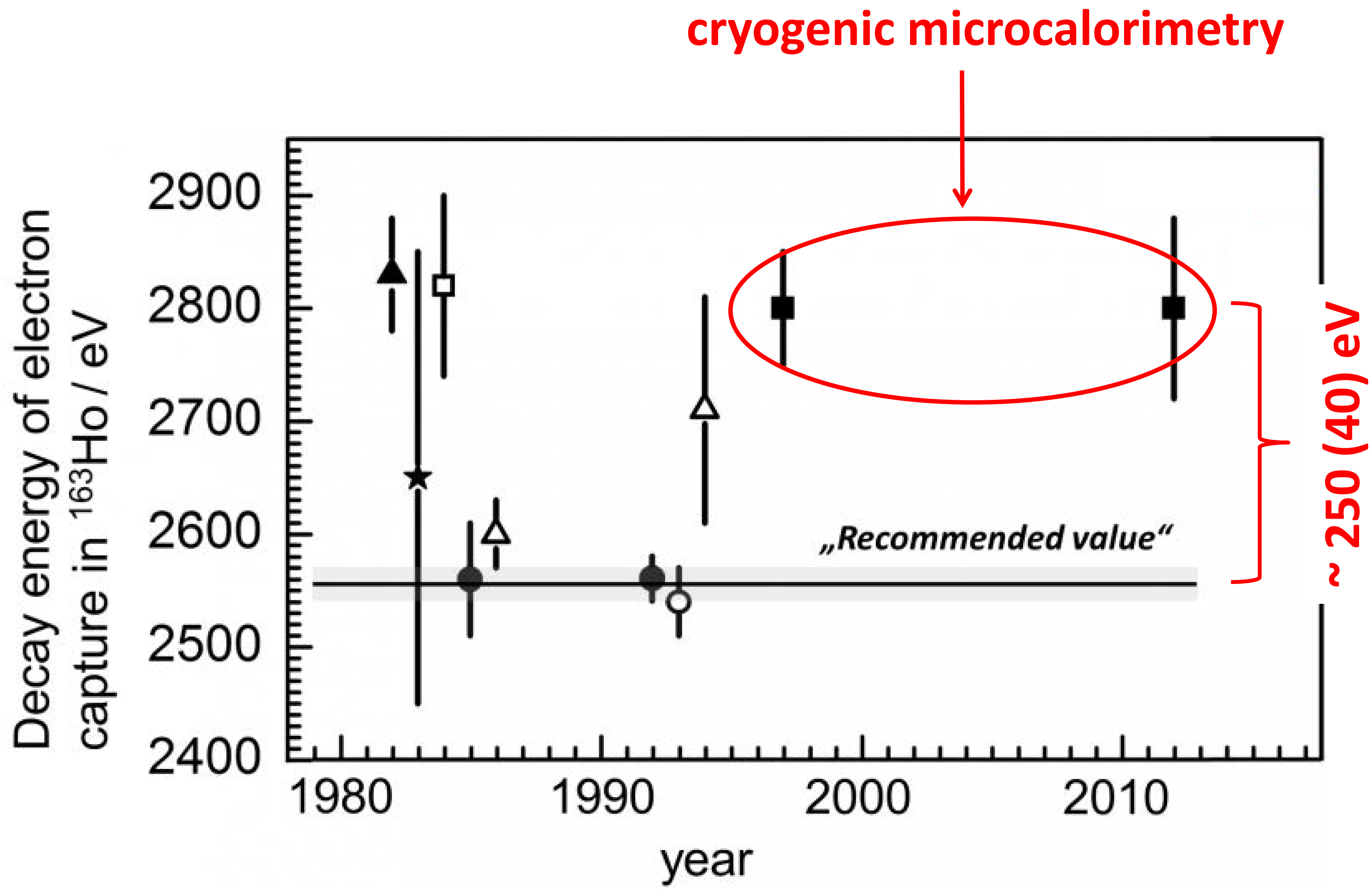


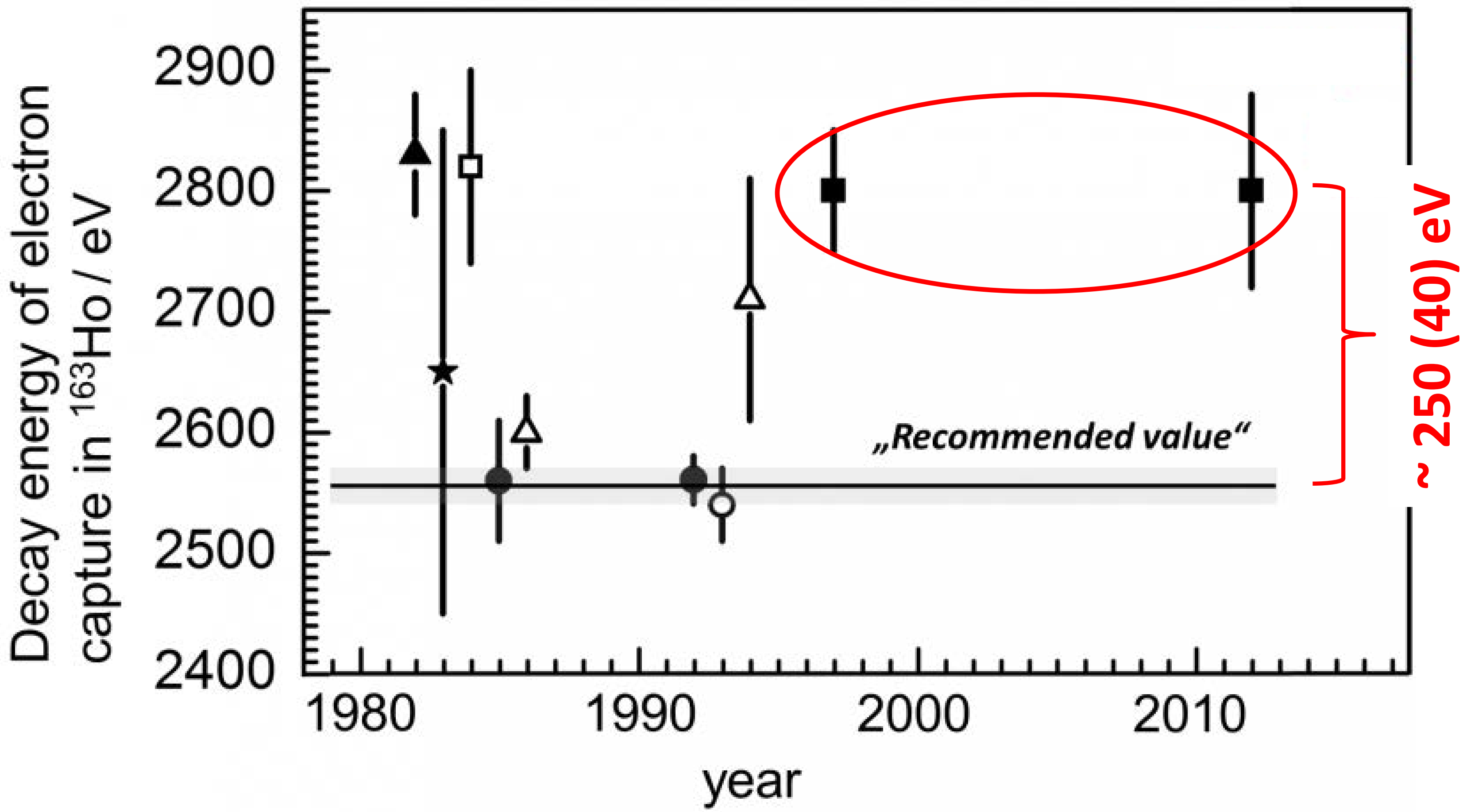
Wire Probe Setup



^{163}Ho wire preparation

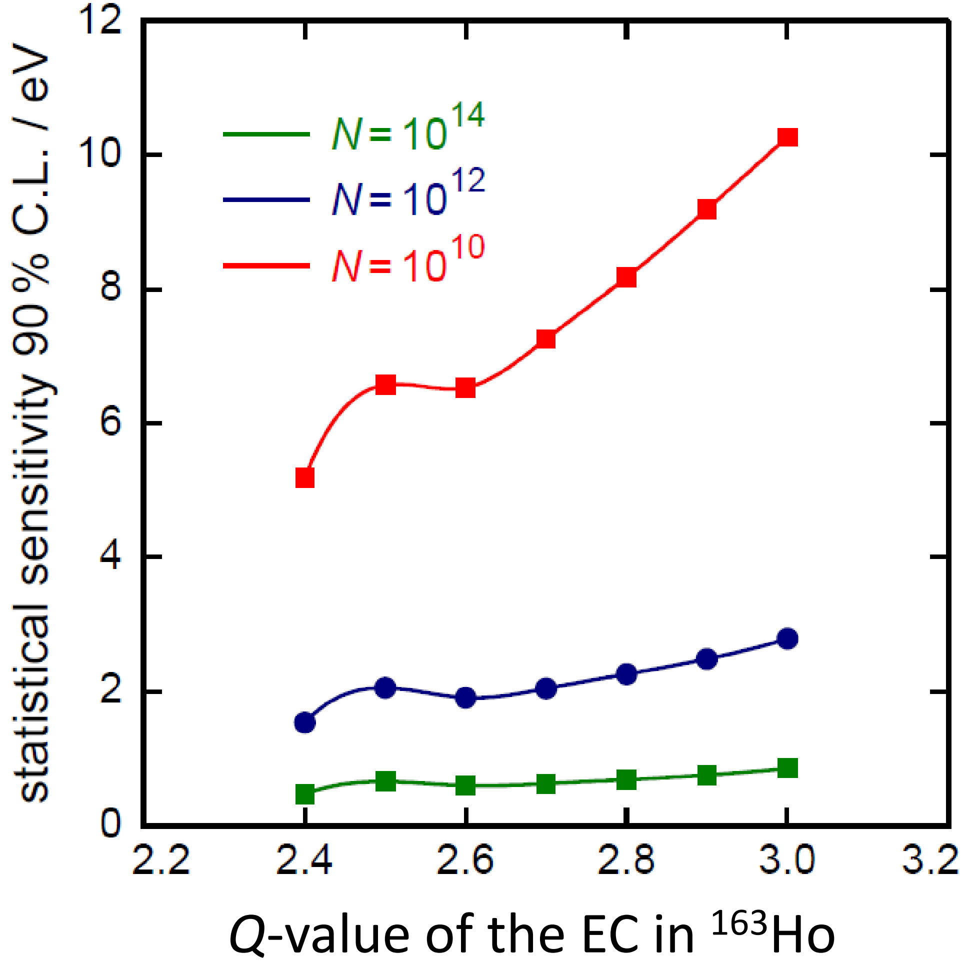



cryogenic microcalorimetry
Decay energy of electron capture in ^{163}Ho / eV
2900
2800
2700
2600
2500
2400
1980
1990
2000
2010
year
„Recommended value“
~ 250 (40) eV



Direct (Penning-trap)measurement of **Q-value** with an uncertainty of **a few ten** eV was demanded

statistical sensitivity to neutrino mass

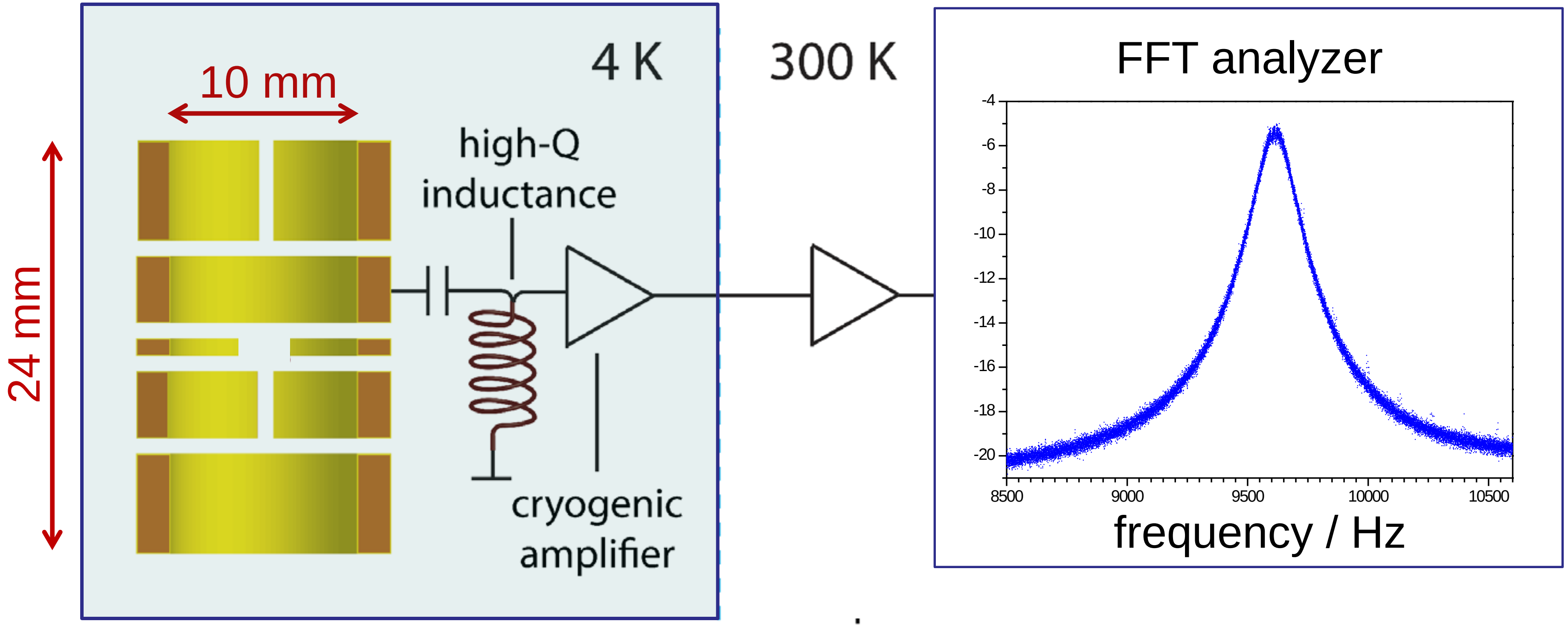


courtesy of Loredana Gastaldo

Mass-ratio measurements at a level of 10^{-11}

Neutrino physics	$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy} + \nu_e + \boldsymbol{Q_{EC}}$
Test of $\boldsymbol{E = mc^2}$	$E = \dfrac{hc}{\lambda} = \Delta m({}^{36}\mathrm{Cl} - {}^{35}\mathrm{Cl} - n)c^2$
Binding energies	$E_B(\mathrm{Xe}^{17+}) = \Delta m(\mathbf{Xe^{26+}} - \mathbf{Xe^{25+}})c^2 - m_e c^2$
g-factor	$\Delta m({}^{48}\mathrm{Ca}^{17+} - {}^{40}\mathrm{Ca}^{17+})$
Thorium clock	$E = \Delta m({}^{229m}\mathrm{Th} - {}^{229}\mathrm{Th})c^2$

Measurement of trap frequencies with PENTATRAP



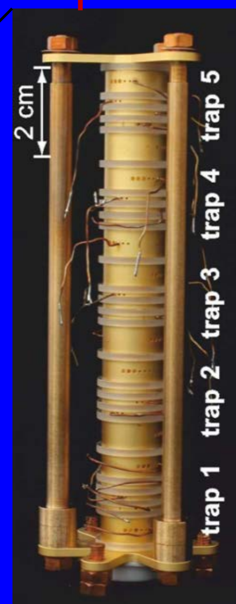
D.J. Wineland & H.G. Dehmelt, *J. Appl. Phys.* 46 (1975) 919 E.A. Cornell *et al.*, *PRL* 63 (1989) 1674 S. Sturm *et al.*, *PRL* 107 (2011) 143003

Measurement of trap frequencies with PENTATRAP

Measurement of trap frequencies with PENTATRAP

Measurement of trap frequencies with PENTATRAP

trap tower

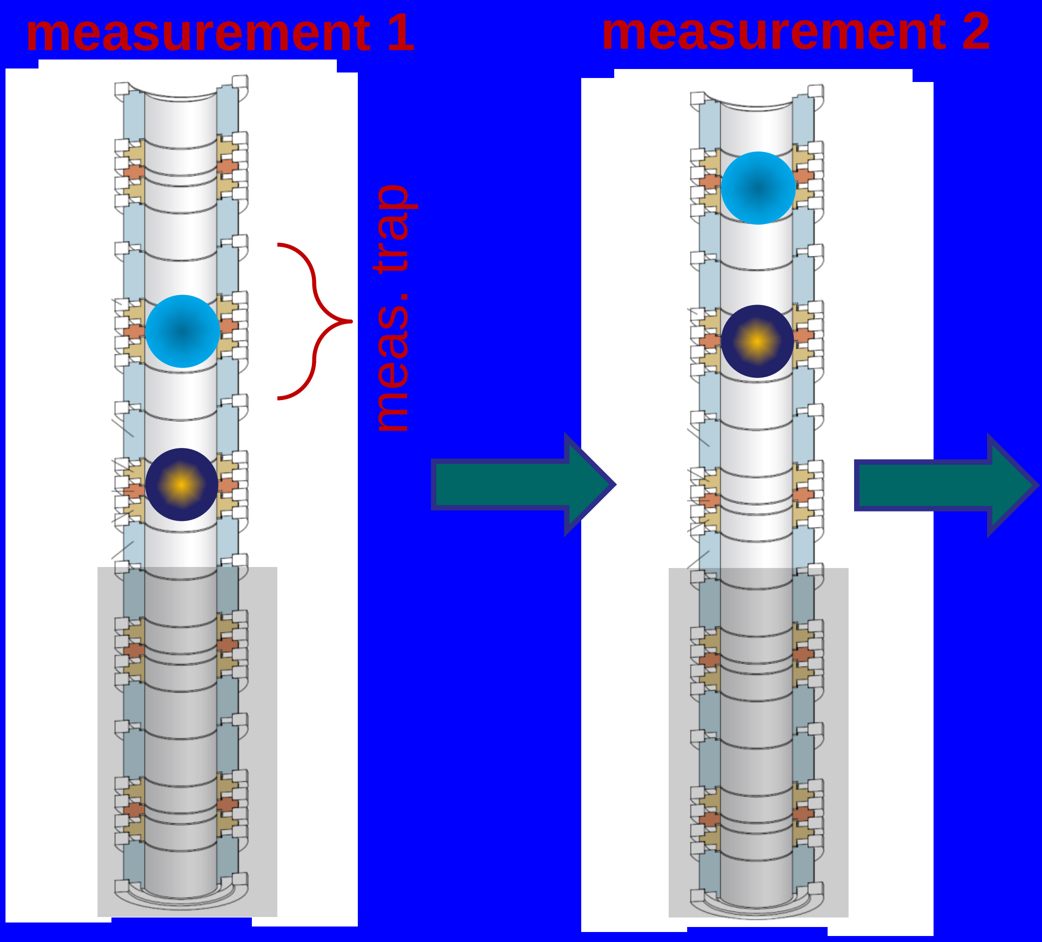


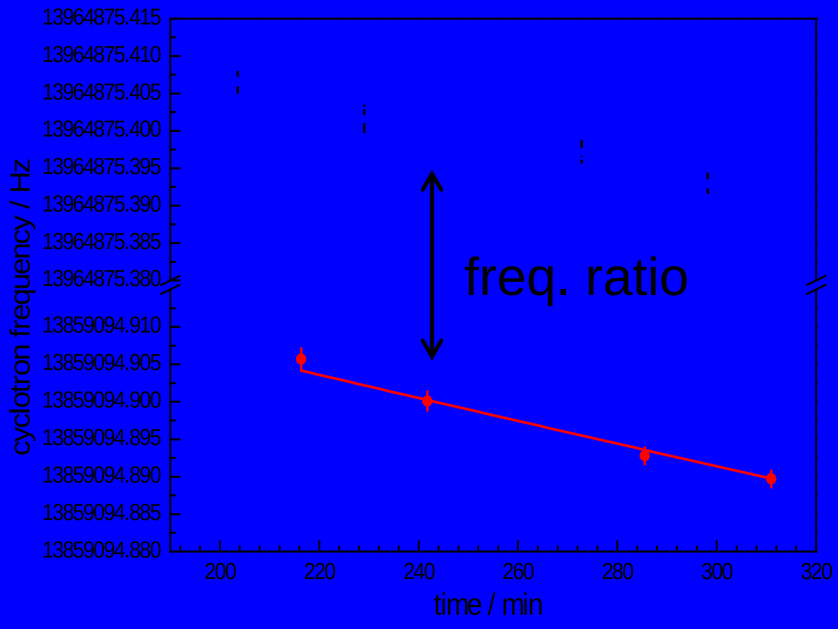
trap electrodes

NbTi toroidal coil

amplifier

$^{131}Xe^{17+}$ vs $^{132}Xe^{17+}$





$^{131}Xe^{17+}$ $^{132}Xe^{17+}$

Final frequency ratio (16 groups of 2-hour measurements each):

$$R = m(^{132}Xe^{17+}) / m(^{131}Xe^{17+}) = 1.007632569093 \pm 2.2E\text{-}11$$

in agreement with the FSU-trap value